Technical Report 2006-03

Puget Sound Nearshore Partnership

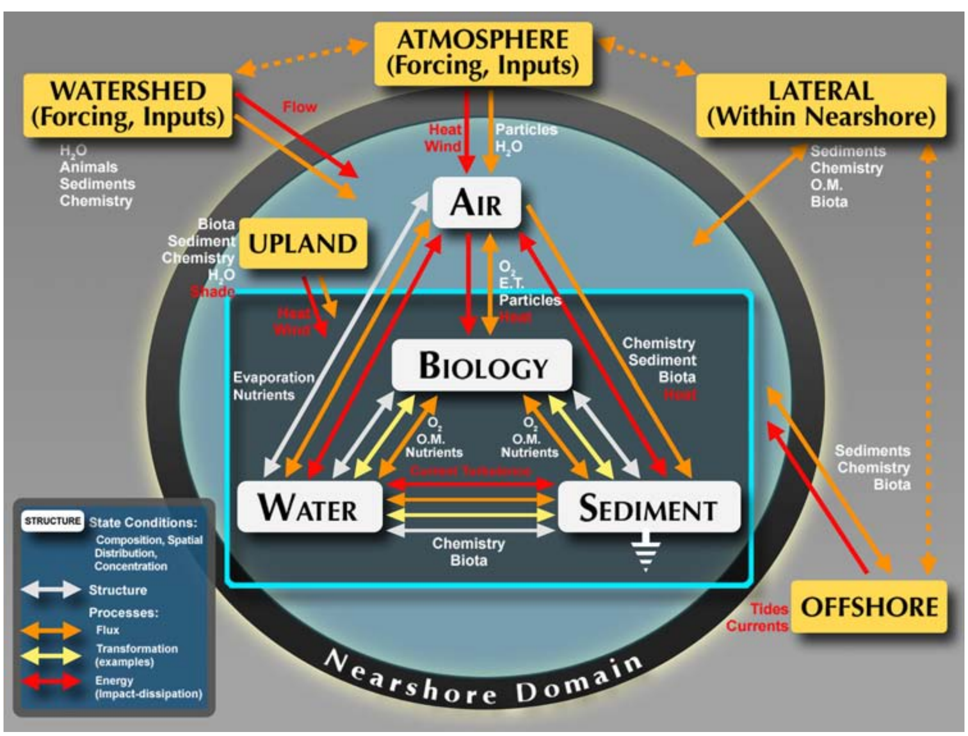
Restoring Our Ecosystem Health

Conceptual Model for Assessing Restoration of Puget Sound Nearshore Ecosystems

Prepared in support of the
Puget Sound Nearshore Partnership

October 2006

Puget Sound Nearshore Ecosystem Research Project
Nearshore Science Team Conceptual Model Working Group
Charles Simenstad, University of Washington
Miles Logsdon, University of Washington
Kurt Fresh, NOAA Fisheries
Hugh Shipman, Washington Department of Ecology
Megan Dethier, University of Washington
Jan Newton, University of Washington



REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
03-2006

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Conceptual Model for Assessing Restoration of Puget Sound Nearshore Ecosystems

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
2006

6. AUTHOR(S)
Megan Dethier, Kurt Fresh, Miles Logsdon, Jan Newton, Hough Shipman, Charles A. Simenstad,

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Puget Sound Nearshore Partnership WDFW - P.O. Box 43145, Olympia Washington 98504-3145
U.S. Army Corps of Engineers - P.O. Box 3755, Seattle Washington, 98124-3755

8. PERFORMING ORGANIZATION REPORT NUMBER
2006-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Washington Sea Grant - 3716 Brooklyn Avenue NE, Box 355060, Seattle Washington 98195-6716
University of Washington School of Oceanography - Box 357940, Seattle Washington 98195-7940
King Conservation District - 935 Powell Ave SW, Suite D, Renton Washington 98057

10. SPONSOR/MONITOR'S ACRONYM(S)
WDFW, USACE, UW

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
2006-01

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
available at www.pugetsoundnearshore.org/index.htm

14. ABSTRACT
The PSNERP Nearshore Science Team has developed a Conceptual Model framework to aid in assessing restoration and preservation measures for nearshore ecosystems in Puget Sound. This model was designed primarily as a synthesis tool to better understand nearshore ecosystem processes and the response of nearshore ecosystems to different stressors or, alternatively, restoration actions. We have designed this model as a framework from which additional, more explicit 'submodels' can be consistently developed that relate to specific nearshore stressors, landscape segments, functions, or restoration designs.

15. SUBJECT TERMS
Nearshore, Puget Sound, marine biota, salmon, cod, pollock, sole, shark, wildlife, marine, watershed, atmosphere, model, scale, process

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
U	U	U	SAR	41

19a. NAME OF RESPONSIBLE PERSON
Bernard L. Hargrave

19b. TELEPHONE NUMBER *(Include area code)*
206-764-6839

Acknowledgements

This model was developed by the Nearshore Science Team (NST) Conceptual Model Working Group. In addition to the primary Working Group participants, Mark Stoermer and other colleagues in the University of Washington, College of Ocean and Fishery Sciences' Learning Center have provided invaluable assistance developing visualizations to aid our explanation of the Conceptual Model (Appendix A). This descriptive version of the Conceptual Model has been reviewed and significantly enhanced by discussions within the NST and input from external scientists during two Conceptual Model Workshops. F. Brie Van Cleve provided invaluable editing to the final draft of this document.

This report was supported by the Puget Sound Nearshore Ecosystem Restoration Project and the U.S. Army Corps of Engineers. Research funding was obtained from Washington Sea Grant, University of Washington.

Citation:

Simenstad, C, M Logsdon, K. Fresh, H. Shipman, M. Dethier, J. Newton. 2006. Conceptual model for assessing restoration of Puget Sound nearshore ecosystems. Puget Sound Nearshore Partnership Report No. 2006-03. Published by Washington Sea Grant Program, University of Washington, Seattle, Washington. Available at *http://pugetsoundnearshore.org*.

Cover: PSNERP–NST Conceptual Model Level 3.

Contents

List of Figures

List of Tables

List of Appendix Tables

Executive Summary

The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) Nearshore Science Team (NST) has developed a Conceptual Model framework to aid in assessing restoration and preservation measures for nearshore ecosystems in Puget Sound, Washington. This framework was designed primarily as a synthesis tool to better understand nearshore ecosystem processes and the response of nearshore ecosystems to different stressors or, alternatively, restoration actions. It may also serve as a tool to plan and guide the scientific elements of the restoration project. The overall goal of the NST for this Conceptual Model is to build a synthetic, ecosystem-process-based understanding about how Puget Sound's nearshore ecosystems "work." This approach is based on the underlying assumption that alterations of natural hydrologic, geomorphologic, and ecological processes impair important nearshore ecosystem structures, which are in turn responsible for ecosystems goods, services, and functions that have societal value. We define ecosystem processes as any interactions among physiochemical and biological elements of an ecosystem that involve changes in character or "state" over time. Because ecosystems are continuously being shaped and reshaped by a variety of physical, geochemical, and biotic processes, they are characterized by changes in state over multiple space and time scales, such as change in chemical composition (e.g., nutrient transformations), biomass (e.g., production and consumption), and movement of material (e.g., sediment transport). The composition, shape, and other characteristics of nearshore ecosystems, such as beach slope and sediment composition, that we may observe at any point in time are the net effect of the interactions of these processes.

Our approach emphasizes ecosystem processes that create the structure of the nearshore (how it works) rather than just the structure itself (how it looks): for instance, restoring the processes that supply natural sediments to beaches and provide for its transport alongshore, as opposed to artificially distributing sediments over the beach. This approach is particularly germane to Puget Sound nearshore restoration because a focus on restoring just the structure of the system without reconstituting the underlying ecosystem processes is considered to be scientifically unsound. Our rationale is as follows:

1. These processes are integrally involved in the nearshore ecosystem functions we desire to recover.
2. Without restoring processes, the long-term maintenance of the structure and associated functions is highly uncertain.
3. Attention only to ecosystem structure is less likely to incorporate the natural dynamics of ecosystems that contribute to their function.

The scope of PSNERP requires that the Conceptual Model address a diverse regional geography and a broad range of ecological communities that characterize different nearshore ecosystems of Puget Sound. This complexity is generally greater than that addressed in other environments where conceptual models have been developed. As a result, we have designed this model as a framework from which additional, more explicit "submodels" can be consistently developed that relate to specific nearshore stressors, landscape segments, functions, or restoration designs. As a result, it differs in several respects from most other conceptual models of interactions among complex ecosystems, by incorporating the following elements:

1. a nested architecture, where complexity and detail increase with increasing steps and "expansions" of consecutive levels;
2. multiple spatial and temporal scales, because restoration actions often involve processes that interact with the nearshore across different scales. Restoration actions themselves may also involve various scales, and the time span (restoration rate) for different actions to reach acceptable performance is critical for restoration planning and assessment;
3. consideration of landscape context, because many problems facing nearshore Puget Sound are associated with the disruption of processes that are contingent on their position or arrangement in the landscape;
4. explanation and prediction of change, in order to predict the outcome of restoring degraded ecosystem processes; and
5. feasibility of translation into a computational model.

While not at present implanted into the existing Conceptual Model, we have also considered how restoration planning practitioners might best use the model as a tool to aid their understanding and assessment of potential sources and magnitudes of impaired nearshore processes, as well as to focus their restoration actions on reconstructing impaired processes.

The nested architecture of the Conceptual Model includes five levels:

Level 1: *Domain*, where the spatial scales and landscape context over which the model will be applied are initialized.

Level 2: *Organization*, where the generic linkages between ecosystem process and structure are developed, incorporating the influences of stressors.

Level 3: *Process*, where all potential processes linking ecosystem elements are identified.

Level 4: *Change/Action Scenario Submodel*, where predictable interactions among ecosystem processes and structures and resulting functions are developed for specific restoration actions.

Level 5: *Timeframe and Variability*, where model dynamics are projected across different temporal scales. This architecture possesses hierarchical characteristics, where everything in a lower (numbered) level constrains the levels above that.

Essentially, the Conceptual Model is designed to identify how nearshore ecosystem processes linking air, water, sediment, and biology components influence ecosystem structure. After defining the Level 1 domain over which the Conceptual Model

will be applied, Level 2 illustrates the interactions among external and internal forcing factors and ecosystem structure and between processes and energy within the designated nearshore domain. Within this domain, we characterize three fundamental ecosystem components—water, sediment, and biology—that interact within the nearshore physiographic setting plus a fourth component—air (atmosphere)—that involves sources and sinks of material and energy to the other three. The Level 4 Conceptual Model expands to include all process linkages among the external forcing factors and nearshore components to include fluxes of materials (e.g., sediments, nutrients, biota), transformations (e.g., chemical changes, evaporation), and energy transfers (e.g., wave, wind, solar).

Level 4 submodels are derived from the higher Conceptual Model framework levels to explain how nearshore processes influence nearshore structure for specific nearshore ecosystem stressors or restoration actions. The submodels provide the critical bridge between the full complexity of ecosystem processes required in Level 3 and just the reduced suite of processes associated with specific changes to nearshore Puget Sound ecosystems. Although the first three levels of the Conceptual Model are built principally around our understanding of natural ecosystem processes, the fourth level is designed to address changes associated with the addition of either stressors or restoration actions involving removal of stressors. For instance, a Level 4 submodel might illustrate the sequence of ecosystem process and structure interactions associated with restoring flooding of a historical tidal marsh by breaching or removing levees. Level 4 submodels also describe how nearshore ecosystem processes and structures are responsible for specific ecosystem functions, such as support of valued species. The design of these submodels also allows users to build scenarios that map backwards to identify nearshore changes that alter or jeopardize valued function.

Thus, Level 4-Change/Action Scenario Submodels can then be used to do the following:

1. evaluate the mechanisms responsible for a specific situation of nearshore ecosystem degradation;
2. predict the response of a nearshore ecosystem to a process-based restoration action; and
3. examine the linkages between nearshore ecosystems and other Puget Sound ecosystems.

Each scenario must be framed to include a description of the current state of the nearshore ecosystem, an explanation of the change or action to nearshore ecosystem structure or processes, and predictions of the ecosystem responses. The submodel is then expressed as a map of interactions among the restored processes, the structural changes, the associated functional response, and the restoration action itself. This level also incorporates the identification of potential constraints, as well as the associated uncertainty in the strength of interactions and in the accuracy of predictions.

Ultimately, the predicted responses in the more focused Level 4-Change/Action Scenario Submodel must be converted back into the conceptual framework of the Level-3 Process model. Level 4 submodels are inherently too simplistic to represent all ecosystem structures and fluxes, transformations, and other processes that must be accounted for in the Level-3 model. At the same time, because submodels focus on more specific interactions among nearshore ecosystem processes and component structures, uncertainty about the scenarios explored in the submodels is potentially greater. The challenge is to construct a Level 3 conceptual model that is fully populated with all possible interactions and contingencies among and within nearshore ecosystem components despite our oft incomplete knowledge. Identifying the patent uncertainties is a primary objective of the conceptual model development, such that monitoring and research can be incorporated into the resulting restoration actions to improve our level of knowledge.

Level 5 of the Conceptual Model is intended to address the temporal variability of ecosystem effects and responses predicted by levels 3 and 4. In developing the Conceptual Model at those levels, it is assumed that the time over which altered nearshore processes operated and structural changes occurred would be integrated over the broad timeline specified by the change/action scenario. Level 1 provides the broader spatial scale of the scenario. Level 5 requires that the user consider the space–time variability over the lifetime of ecosystem change generated either by natural processes or in response to a stressor or restoration action. This will be particularly important in projecting both the spatial and temporal influence of a restoration or preservation action, as well as comparing that extent between natural ecosystem processes and more structural or artificial approaches.

The NST anticipates that this Conceptual Model framework can be extended beyond the context we envisioned for understanding the interactions among nearshore structure, processes, and valued ecosystem functions and services. For instance, it may serve at least four purposes:

1. serve as a "checklist" for evaluating interconnectivity beyond the nearshore processes, structure, and function of direct interest;
2. develop an understanding of broad ecosystem or landscape- scale interactions and constraints upon nearshore processes and how these processes might respond both to stressors and to restoration actions;
3. provide a systematic means to compare the outcome of alternative restoration scenarios; and
4. constitute a framework that is convertible into a more quantitative model in the future.

One advanced tool that could evolve from the current Conceptual Model is an interactive computer application or web-based interface designed to assist a user's exploration of nearshore Puget Sound restoration. It would integrate ecological theory about the way nearshore ecosystems "work," advanced visualization technology, and object-orientated computer programming and dynamic model construction. The model would be designed as an interview with users with any level of expertise, requesting input and interaction while providing educational tools and illustrations of important ecological processes. Our goal for such a model would be to inform and assist the user in forming their own conceptual model as to how the complex interactions between ecosystem processes affect nearshore restoration outcomes.

Introduction

This report describes a Conceptual Model framework for assessing restoration actions under the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP). The PSNERP Nearshore Science Team (NST) developed this Conceptual Model primarily as a synthesis tool to plan and guide the scientific elements of the restoration program. Although the Conceptual Model may have diverse applications beyond the NST needs, such as an interactive, internet-based tool for restoration practitioners (see Appendix A), this version of the Conceptual Model is designed principally for the NST's technical examination of nearshore ecosystem processes and the response of nearshore ecosystems to restoration.

This document should be viewed in concert with two other NST products that help provide a broader context to the restoration goals and approaches of the Puget Sound Nearshore Partnership ("Nearshore Partnership"): Guiding Restoration Principles (Goetz et al. 2004) and the Guidance for Protection and Restoration of the Nearshore Ecosystems of Puget Sound (Fresh et al. 2004). This Conceptual Model has evolved considerably since it was first developed in early 2002. Development of the Conceptual Model involved defining its purpose, developing its structure and application, designing the model hierarchy, defining a glossary of terms, and describing a first-order "operational level" model. (See Appendix B for the PSNERP-NST glossary that defines terms used in all these documents.)

Several important factors should be kept in mind when reviewing the Conceptual Model:

1. It has a very specific audience—as described herein, the model is principally scientific and directed toward the level of knowledge represented by the NST and scientific collaborators. However, the model may be used in different forms by the PSNERP program. For example, it may be easier to transmit to lay audiences the concepts represented by the model by reducing its schematic complexity, although that will not be the form that the NST uses to address the issue in greater detail.
2. It is an evolving tool—as conceptual models are seldom finished products, the Conceptual Model is designed as a working tool for the NST and will, therefore, continue to evolve as the NST applies it to progressively more detailed and different restoration scenarios;
3. It initially is descriptive—at this stage, the Conceptual Model is purely a descriptive tool and should not be interpreted as a quantitative model in any respect; however, the model was intentionally designed to evolve into a computation model;
4. It is oriented toward directed actions—while the model is inherently based on our understanding of the relationship between unimpacted ecosystem processes and structure, it is intended to conceptualize cause-and-effect relationships, such as changes due to environmental stressors or to restoration actions.

Conceptual Models

Developing a conceptual model is fundamentally important to a comprehensive restoration program such as proposed under PSNERP. While conceptual models of complex ecological systems serve multiple purposes and applications, they principally define the scope of a problem and describe the causes, interactions, and effects underlying environmental change (National Research Council [NRC] 1990, 1995). In the case of ecosystem restoration, conceptual models that explain working hypotheses about system form and function may be essential for reducing uncertainty about predicting the consequences of alternative restoration actions (de Wit 1993, Huggett 1993).

These simple, non-quantitative models are an effective means for developing consensus around a set of causal hypotheses that explain the effects of major anthropogenic stressors on nearshore ecosystems. Each model identifies the attributes in the natural systems that can best indicate changes due to the stressors. Each model also delineates the ecological linkages between the stressors and the attributes and the most appropriate measures for each of the attributes. Developing a consensus regarding the components and linkages in the conceptual models is the first step in the process of reaching agreement on specific hydrological, ecological, and biological measures of restoration success, and for designing a regional, performance-based ecological monitoring program. Conceptual models have been widely used for similar purposes in other regions of North America (e.g., Gentile 1996, Rosen et al. 1995).

Conceptual models can be valuable tools to express current understanding about critical components and processes regulating ecosystems, articulate assumptions about how components and processes interact, and identify gaps in knowledge (Walters 1986). They can be used for a variety of purposes: for example, to elucidate a general, relative abstract state of understanding about a system or complex process; to develop the rationale for the design of studies to test hypotheses or assumptions; and to provide the basic structure of a computational model. Conceptual models can also be very helpful in applied studies of ecological systems, where the objective is to predict the system's response to a particular stressor or remedial action. Also, conceptual models have much broader applications beyond environmental science and engineering, including social science and medicine, where they are used to link information and data and generate or test the relationships between them. A working conceptual model should at least provide insight into the behavior of the system being studied. More elaborate conceptual models (e.g., GIS systems) actually define the flows of information. They are often considered critical to scientifically based monitoring plans (NRC 1995).

In the most general sense, effective conceptual models typically include the following components (see Glossary for more detailed definitions):

- objects
- properties
- relationships
- actions
- constraints, and
- behavioral expectations

In applying a general conceptual model to restoration actions in nearshore Puget Sound, we could interpret *objects* to be nearshore ecosystems (or habitats, if we are focusing narrowly on certain species requirements), *properties* would be their physicochemical and biological attributes, *relationships* would represent the ecosystem processes and exchanges (e.g., fluxes), *actions* would be restoration or other manipulations, *constraints* on restoration would include historical change or socioeconomic limitations, and *behavioral expectations* from our *actions* would be our predictions of restoration outcomes.

Goal and Underlying Hypothesis

The overall goal of the NST for this Conceptual Model is *to build a synthetic, ecosystem-process-based understanding about how Puget Sound's nearshore ecosystems work.* This goal is based on the NST's underlying scientific hypothesis:

> Alterations of natural hydrologic, geomorphologic, and ecological processes impair important nearshore ecosystem structure and functions.

Our goal focuses on (1) ecosystem processes—"how it works"—rather than the structure—"how it looks"—of nearshore ecosystems, and (2) how the interaction between processes and structure (Figure 1) influences ecosystem functions—"how we benefit from it" (i.e., the goods and services of Puget Sound) or, conversely, "how does it affect our ability to take advantage of those goods and services"). As described in the NST Guiding Restoration Principles (Goetz et al. 2004), ecosystem processes are any interaction among physicochemical and biological elements of an ecosystem that involve changes in character or "state" over time. Ecosystems are not naturally static in space and time but are continuously changing, being shaped and reshaped by a variety of physical, geochemical, and biotic processes. Thus they are characterized by changes, including chemical composition (e.g., nutrient transformations), biomass (e.g., production and consumption) and movement of material (e.g., sediment transport). The functions of an ecosystem can be expressed either as material that an ecosystem captures, produces, or changes, or as the result of interactions between ecosystem processes and its structure (Figure 1; Hobbie 2000, Benda 2004).

As one example (Figure 2), a valuable function of some Puget Sound beaches is the production of forage fish, such as Pacific sand lance (*Ammodytes hexapterus*), that are extremely important to upper trophic levels of Puget Sound food webs (Simenstad et al. 1979). Although the reason that sand lance may have adapted to spawn on a particular beach is still relatively unknown, and this adaptation may be a function of large-scale processes (e.g., larval transport), characteristics of beaches that do support sand lance spawning are consistent and suggest that restoring those conditions could support potential sand lance production. The function for a specific beach ecosystem can be expressed both as the biomass of larval sand lance that hatch from the eggs as well as the biomass of larvae or juveniles that leave the beach area. In this Conceptual Model, we think of the latter process as producing a biological output.

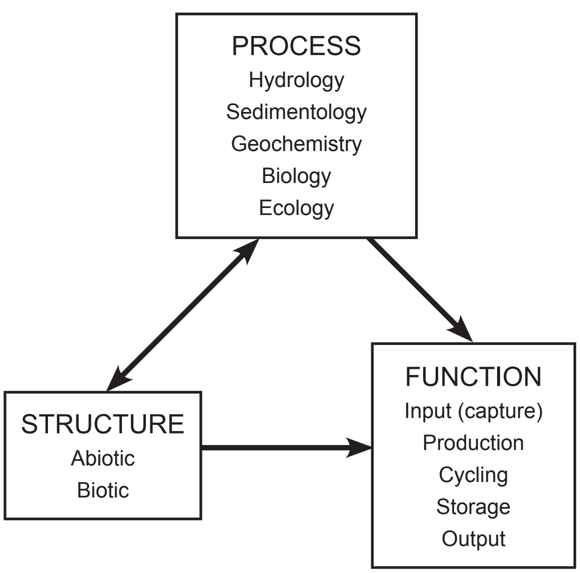


Figure 1. Interactions among ecosystem processes, structures and functions. Ecosystem interactions addressed in the Conceptual Model occur primarily between processes and structure, which both in combination and separately influence valued ecosystem functions.

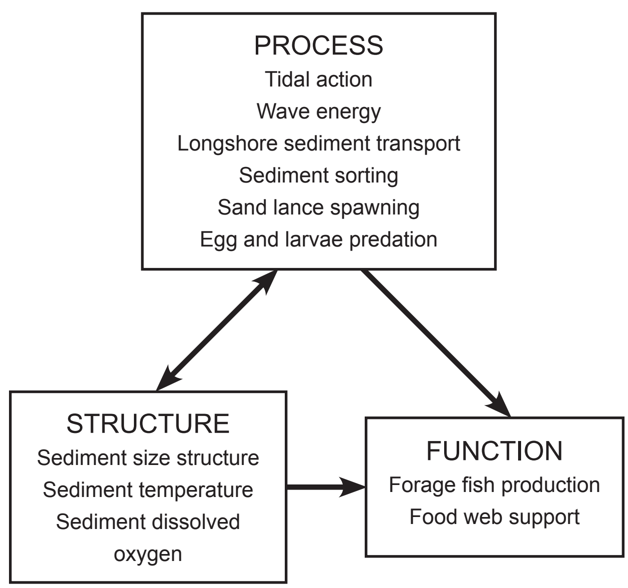


Figure 2. Example of interactions among ecosystem processes, structures, and functions represented by the role of nearshore Puget Sound beaches in sustaining Pacific sand lance (*Ammodytes hexapterus*) populations.

The *structure* of the beach ecosystem that is largely responsible for that production and output is the specific substrate size composition (e.g., fine gravel and coarse sand), intra-gravel temperature, and the natural, high intertidal beach profile, including overhanging vegetation. We presume that some structural attributes can be related to sand lance spawning and egg survival. These structural characteristics are the result of interacting *processes* of nearshore tidal action and wave energy (hydrological), beach sediment deposition and transport (sedimentation), and the biological and ecological processes involved with vegetation, colonization, growth, succession, and senescence. Structure can be defined at several scales, but we typically incorporate the scales of shoreforms (Shipman in prep.) ranging from <1 km to small features (e.g., patches of differing sediment or vegetation) just a few m in dimension. While full recovery of the function of a beach for Pacific sand lance production can be attempted by just re-creating the natural structure of the high intertidal beach, the long-term success and effectiveness of this action is highly uncertain without commensurate restoration of the fundamental beach processes that maintain that structure (e.g., natural tidal inundation and wave energy, sediment input and transport, and riparian vegetation shading).

The Conceptual Model is intended to show how and why the structure of beaches, wetlands, and other nearshore environments changes in response to natural forcing factors, anthropogenic stressors, and potential restoration actions. Understanding the mechanisms, patterns, and rates of ecosystem change is essential for restoration because Puget Sound's nearshore ecosystems are naturally dynamic, and most natural functions of the nearshore derive from that dynamism. The state of science about Puget Sound nearshore ecosystems supports the following premise:

> Dynamic natural processes, such as the forces (e.g., storms) that maintain seasonal variability in sediment movement and biological structure, are important for maintaining valuable characteristics and functions of Puget Sound, including clean water, viable salmon populations, and estuarine wetlands.

Approach

As implied by the NST goal for the Conceptual Model, our approach is to emphasize ecosystem processes that create the structure of the nearshore, rather than just the structure itself. This approach is particularly germane to Puget Sound nearshore ecosystem restoration because a focus on *restoring just the structure of the system without reconstituting the underlying ecosystem processes is considered to be scientifically unsound.* There are three reasons for this conclusion:

1. the processes are inherently involved in the functions we desire to recover;
2. without restoring processes, the long-term maintenance of the structure and associated functions is highly uncertain; and
3. incorporating or accepting natural ecosystem dynamics is less likely when considering only ecosystem structure.

For instance, one important application of this Conceptual Model is not simply to describe fish habitat but to characterize the processes that form and sustain the habitat of Pacific salmon (*Oncorhynchus* spp.) as a dynamic feature in the Puget Sound landscape over time (Fresh et al. 2004).

With this approach, we have also adopted the following perspectives on this Conceptual Model:

1. Although the Conceptual Model will identify the processes that account for a fully functioning nearshore ecosystem, it is not designed to define an "optimum" ecosystem state or an index of "ecosystem health."
2. It will identify appropriate shifts in processes that will capture any condition of natural, degrading, or restoring ecosystems, rather than define and compare the structure of historical, existing, or restored ecosystems.
3. It will represent in sufficient detail the variability in both natural and anthropogenic processes that create the range of nearshore ecosystems; it will not necessarily represent the total range of nearshore conditions found in Puget Sound.

The NST anticipates that the Conceptual Model may be used beyond the context we envisioned for understanding the interactions among nearshore structure, processes, and valued ecosystem functions and services. However, we anticipate that it will serve at least four purposes within the context of Nearshore Partnership:

1. serve as a "checklist" for evaluating interconnectivity among nearshore processes, structure, and function beyond those of direct interest;
2. develop an understanding of broad, ecosystem or landscape-scale interactions and constraints upon nearshore processes and of how these processes might respond both to stressors and to restoration actions;
3. provide a systematic means to compare the outcome of alternative restoration scenarios; and
4. constitute a framework that is convertible into a more quantitative model in the future.

The Conceptual Model as a "Framework"

The scope of PSNERP requires that the Conceptual Model address a diverse regional geography and a broad range of ecological issues specific to different nearshore ecosystems of Puget Sound. This complexity is generally greater than that addressed in other environments where conceptual models have been developed. As a result, we have designed our model as a "framework" from which additional, more explicit "submodels" can be consistently developed and applied to specific nearshore stressors, landscape segments, functions or restoration designs. This is analogous to the approach taken by Newton et al. (2000) in the Puget Sound Ambient Monitoring Program (PSAMP), wherein a conceptual model for environmental monitoring is based upon a matrix of natural and anthropogenic stressors, inputs to Puget Sound and components of human and ecosystem health. As in our more graphical, process-based Conceptual Model, the PSAMP Conceptual Model developed graphical submodels that illustrate the existence and strength of linkages in different segments of the matrix.

The following text will describe not only the overall Conceptual Model structure and its application as a series of submodels to several specific examples.

Model Structure

Although we draw on many commonalities, several characteristics distinguish the NST Conceptual Model of the Puget Sound's nearshore ecosystems from most other conceptual models of interactions among complex ecosystems:

1. *Nested architecture*: The model is organized in a nested structure, meaning that complexity and detail increase with increasing steps and "expansions" of consecutive levels. At its most complex stage, it represents a system of individual (nearshore ecosystem) states represented across multiple scales of space and time. If properly represented, the user should be able to look inward at the detail and outward at an integration of the surrounding environment, providing a simultaneous view of the system as a whole and in parts (Allen and Starr 1982).
2. *Incorporation of spatial and temporal scales*: We explicitly integrate two important aspects of nearshore ecosystems—numerous spatial scales, and temporal variation—that are often only peripherally incorporated into conceptual models, if at all. Multiple spatial scales must be accommodated because restoration actions often involve processes

that interact with the nearshore across different scales. The restoration actions themselves may also involve various scales. Temporal variation is an important aspect of the NST Conceptual Model because the timespan (restoration rate) for different restoration actions to reach acceptable performance is critical for restoration planning and assessment.

3. *Consideration of landscape context (landscape heterogeneity and arrangement)*: Many problems facing Puget Sound are associated with the disruption of processes that are contingent on their position or arrangement in the landscape (e.g., where this disruption occurs influences the impact on a nearshore ecosystem function). The landscape context is important because (a) the nearshore zone spans many distinct environmental gradients, along which ecosystem processes are often concentrated; and (b) the effect of many nearshore processes and the distribution of ecological communities vary as a function of both landscape structure (e.g., patches, mosaics, corridors) and the disruption of those elements across space. This requires that the Conceptual Model account for not only the spatial scale of a restoration action but also the position of the action relative to other landscape elements.
4. *Explanation and prediction of change*: Because this model's most important application is to help us understand how ecosystem responses vary with natural and anthropogenic change, it should both explain historical change in Puget Sound's nearshore ecosystems and its consequences, and predict the outcome of restoring degraded ecosystem processes.
5. *Feasibility of translation into a computation model*: While this is inherently a conceptual model in its present form, we have attempted to design the model so that it could be developed in to a computational model in the future.
6. *Provision of a pathway to assess the consequence of ecosystem restoration*: Although the model is not explicitly designed to be a tool for restoration planning per se, we acknowledge that a more accessible form of the model could help restoration practitioners to assess the potential source and magnitude of impaired nearshore processes, as well as focus restoration actions on reconstructing impaired processes.

Conceptual Model

Model Architecture

The NST Conceptual Model is designed to incorporate increasing complexity and accommodate variability in spatial, temporal, and natural and anthropogenic change in Puget Sound's nearshore ecosystems. The five levels in the PSNERP–NST Conceptual Model's nested architecture are as follows:

Level 1 Domain: Initialization of the spatial scales and landscape context over which the model will be applied.

Level 2 Organization: Organization of the generic linkages between ecosystem process and structure, incorporating the influences of stressors on both.

Level 3 Process: Incorporation of all potential processes linking ecosystem elements.

Level 4 Change/action scenario submodel: Development of predictable interactions across pressure–state–response sequences associated with restoration or other actions directed toward nearshore processes.

Level 5 Timeframe and variability: Projection of model dynamics across different temporal scales (seasonal, interannual, long-term processes and frequencies; stochastic, catastrophic events; persistence)

This architecture possesses hierarchical characteristics—that is, everything in a lower (numbered) level constrains the levels above that.

Level 1: Domain

Spatial Scales and Landscape Context

In accordance with the broad scope of the nearshore as defined by Nearshore Partnership (Fresh et al. 2004), the Conceptual Model must be able to accommodate multiple spatial scales and landscape settings (Figure 3). Ecosystems are grouped into the following "process domains" in which both ecosystem structure and processes occur along the energy and salinity gradient from the head of tide, at the estuary–watershed margin, to ocean:

1. tidal floodplain, including tidal freshwater and oligohaline channels;
2. estuarine delta;
3. nearshore estuarine; and
4. exposed marine.

Within any of these process domains, the Conceptual Model must be able to address the interaction among ecosystem processes, structures, and functions at multiple spatial scales. We have very simply classified three domains—*local*, *process,* and *landscape*—with the following definitions:

1. A *local* domain is confined within ecological units, such as marshes, beaches, drift cells, and so forth. It typically encompasses meters to hundreds of meters (e.g., cross-beach, short lateral beach, tidal slough).

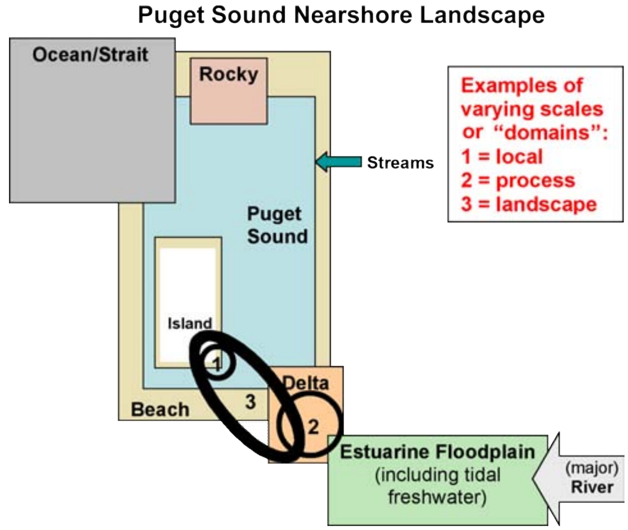


Figure 3. PSNP-NST Conceptual Model Level 1: Domains of spatial scale and landscape position over which NST Conceptual Model is applied. The model can be applied to spatial relationships within, and at boundaries and intersections, between and among components (boxes). We include non-tidal portions of rivers and streams and coastal watersheds only as origins of forcing inputs and exchanges. Differences in scales (sizes of boxes) among components vary, and are not intended to be fixed, as represented in this diagram. Freshwater inputs to Sound via groundwater and small features such as back-barrier marshes, small stream-mouth estuaries, and rocky knobs in deltaic environment are not represented at this scale. Island is geographical feature of significance, but does not in itself reflect any shoreline type not already represented.

2. A *process* domain encompasses multiple ecological units. It typically ranges hundreds of meters to kilometers (e.g., along-beach within geomorphic units/salinity regimes).
3. A *landscape* domain occurs between and among domains. It typically spans kilometers to tens of kilometers, with emphasis on interactions among "domains."

Because these generic, process-based domain classifications can occur throughout Puget Sound across varying scales, the Puget Sound is often considered an inland sea complex of estuaries (or sub-estuaries). While 11 river basins draining the Cascade or Olympia mountain ranges are associated with major estuarine deltas, hundreds of other small rivers and streams distributed around the Sound also provide estuarine conditions on a local scale. The estuarine nearshore and exposed marine nearshore link delta and smaller estuarine features together at scales that vary from local to landscape. A variety of geomorphic forms ("shoreforms") are associated with different ecological units and process domains, as described in the PSNERP–NST Typology (Shipman in prep.). Because oceanographic attributes of Puget Sound, such as water circulation, can influence the magnitude and range of nearshore responses to external and internal forcing

(e.g., tidal range), an important aspect of establishing the *domain* of the Conceptual Model includes identifying the Puget Sound basin(s) under consideration. Burns (1985) suggested the following division of Puget Sound basins:

1. southern
2. main
3. central
4. Whidbey
5. Hood Canal
6. northern Puget Sound (Strait of Georgia)
7. eastern Strait of Juan de Fuca

Level 2: Organization

The model organization describes interactions (1) among external and internal forcing factors and ecosystem structure and (2) between processes and energy within the designated nearshore domain (Figure 4). Forcing factors at the regional scale originate primarily as inputs from adjacent watersheds and the atmosphere. Significant exchanges also occur between the nearshore and both lateral (adjacent nearshore) and offshore ecosystems. Within the nearshore domain (dashed circle), we characterize three components—water, sediment, and biology—that occur in the "wet" physiographic setting (e.g., extreme high water (EHW) to deepest limit of photic zone), but that are influenced by terrestrial and atmosphere forcing factors. In addition, a fourth component—air (atmosphere)—is involved as a source and sink of material and energy. As will be explained in ensuing level descriptions, each of these components is complex in its own right and includes structural characteristics and processes within the domain and spatial scales of the designated nearshore. Essentially, the NST Conceptual Model is designed to identify how ecosystem processes between air, water, sediment and biology components influence the internal structure of those components.

We have also designated the ultimate domain within which nearshore and adjoining ecosystems exist—the human domain—that encompasses social, cultural, and economic influences on our values and attitudes about the intrinsic functions of these ecosystems. While we do not explicitly include these human dimensions in the Conceptual Model, we acknowledge that it is the ultimate context within which nearshore ecosystem processes operate.

Various anthropogenic stressors can originate from external and nearshore sources, and even within the "wet" portion of the nearshore. Prominent nearshore stressors can originate both within and outside the nearshore (Table 1).

Level 2 provides the framework through which the desired outputs, scope, and scale of a limiting processes analysis (see Guidance Document, Fresh et al. 2004) may be defined and the possible consequences of restoration actions explored.

Level 3: Process

The process level of the Conceptual Model (Figure 5) expands the process linkages among the external forcing factors and nearshore components (i.e., water, sediment, biology, and air) to include fluxes of materials (e.g., sediments, nutrients, biota), transformations (e.g., chemical changes, evaporation), and energy transfers (e.g., wave, wind, solar). While we consider the direction of fluxes, transformations, and energy transfers

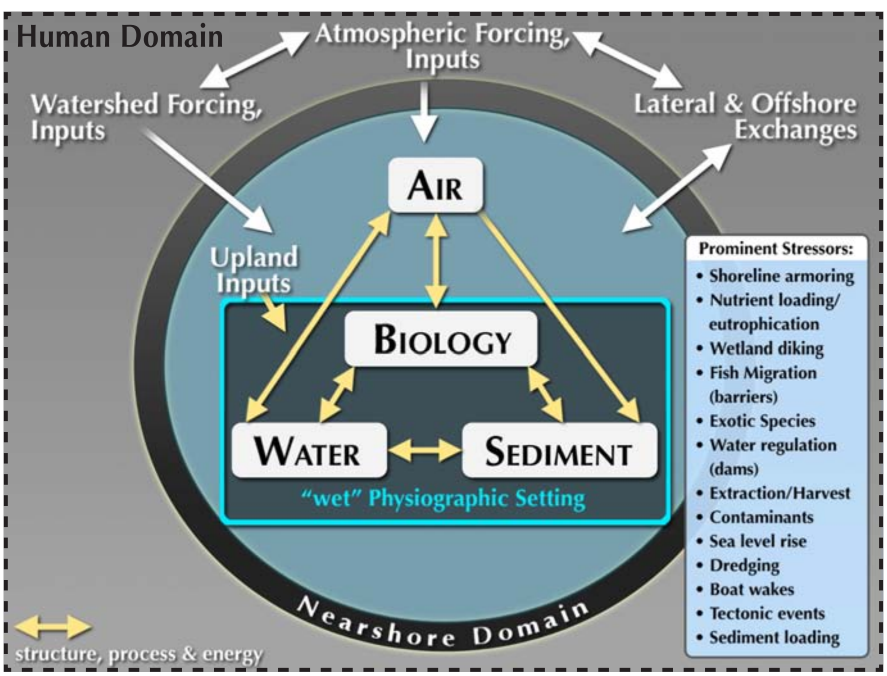


Figure 4. PSNERP–NST Conceptual Model Level 2: *Organization* of nearshore ecosystem relative to external and internal forcing, structure and processes.

Table 1. External and internal sources of stress to the Puget Sound nearshore. See Newton et al. (2000) for a more detailed list of stressors.

Stressor	External	Internal
Nutrient loading/eutrophication	X	X
Sea level rise	X	
Tectonic events	X	
Boat wakes	X	X
Water regulation (dams)		X
Shoreline armoring		X
Wetland diking	X	X
Fish migration (barriers)	X	X
Exotic species		X
Extraction/harvest	X	X
Contaminants	X	X
Dredging	X	X
Sediment loading	X	?

(dashed arrows, Figure 5) to be relatively complete, the actual labels are only examples of the material, energy, and changes that might occur among the four components. In the case of energy, we also include dissipative changes (e.g., energy absorption). And, in the case of sediments, the removal of some sediments from circulation within the ecosystem (e.g., burial) constitutes an internal "sink." At this level, there is no temporal context. Instead this level represents the total cumulative suite of linkages among processes and structures that constitute the nearshore system.

All four nearshore components contain extremely complex internal processes and structures (box patterns, Figure 3). In developing this model, we found that we could address some of the hardest questions (i.e., those asking 'what shapes nearshore ecosystems?') by dissecting these component boxes. The submodels explore these structural and process relationships within and between the components. As an example of the internal structure and processes within and between nearshore components, we expanded upon the response of the biology component to changes in the sediment component (Figure 6).

The structure of the sediment component is determined by sediment attributes (grain size, redox, dissolved oxygen [DO], salinity, etc.), sediment depth, and elevation along beach gradient all integrated over time steps (e.g., tidal cycles, diel cycles, and seasonal cycles). Geochemical and other non-biological processes that occur within sediments characterize changes among the sediment attributes and other constituents over space (e.g., sediment depth) and time. Similarly, the biology component has both structural attributes of living organisms (e.g., bacteria, diatoms, meiofauna, and macrofauna) and internal biological processes (e.g., production, consumption, and respiration) that to some degree regulate the dynamics of the organisms associated with the sediment (benthic, epibenthic).

Some of the most important linkages are between the Sediment and Biology components because sediment dynamics and the physicochemical conditions within beach, marsh, and other nearshore sediments play a significant role in structuring biological communities and associated processes. For example, dissolved oxygen (DO) in sediments can directly correlate with

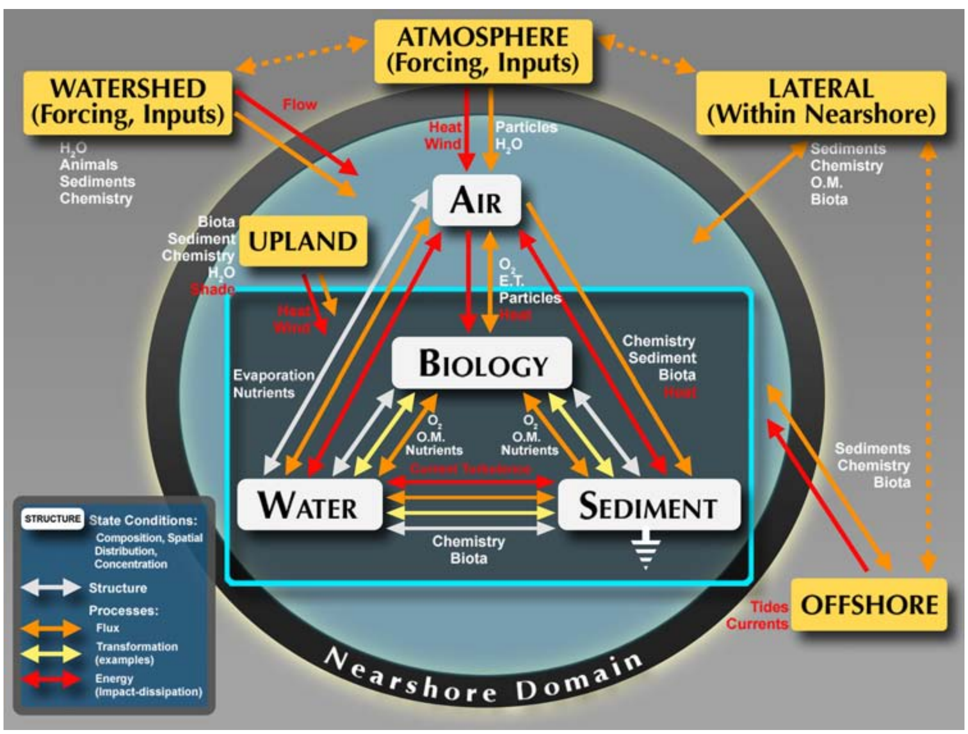


Figure 5. PSNERP–NST Conceptual Model Level 3: Processes affecting the structure of air, biology, water and sediment components, with examples of fluxes, transformations, and energy interactions among these primary components of the nearshore. The oval shaded area represents the suite of interactions between sediment and biology components discussed in the text as examples of Level 3. ET = evapotranspiration; OM = organic matter.

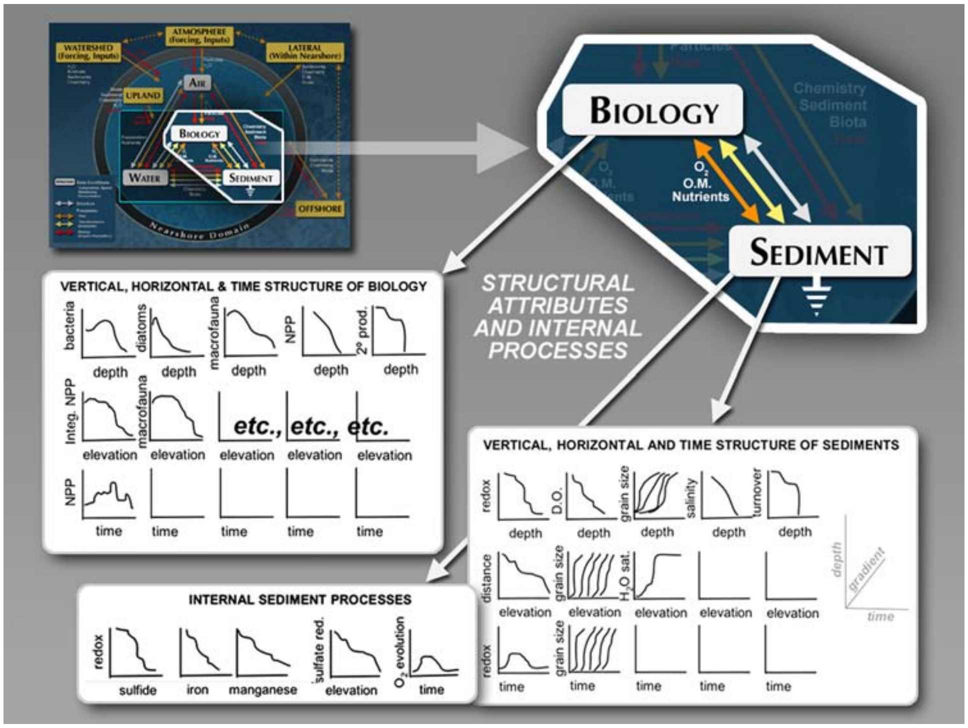


Figure 6. PSNERP–NST Conceptual Model Level 3. Example illustrating the interactions between, as well as the structure and processes within, the sediment and biology components that control the response of nearshore biology to changes in nearshore sediments.

the distribution of certain macrofauna species in the sediment. Specifically, sulfate reduction processes can explain patterns in net primary production (NPP).

Level 4: Change/Action Scenario Submodels

In theory, Level 3 of the Conceptual Model would be populated by all known patterns of structural attributes as well as all process relationships of nearshore ecosystems at different spatial and temporal scales. However, generating scenarios to illustrate these relationships is limited because we lack sufficient data and information specific to the Puget Sound to populate the model. Furthermore, while our primary interest is in representing stressed systems and predicting restoration actions, most existing information characterizes relatively unstressed ecosystems. As a result, the Conceptual Model incorporates linearly constructed pressure–state–response submodels built on keystone scenarios of nearshore ecosystem change. These changes can represent ecosystem response to a stressor or the removal of a stressor followed by full or partial restoration of natural processes. The submodels are derived from the Conceptual Model framework to explain how nearshore processes influence nearshore structure. At a minimum, submodels can be used to (1) evaluate the mechanisms responsible for a critical case of nearshore ecosystem degradation, (2) assess the response of a nearshore ecosystem to a process-based restoration action, and (3) examine the linkages between nearshore ecosystems and other Puget Sound ecosystems.

Each scenario must be framed as follows: (1) an explicit definition of the *scenario*, (2) description of the extant state of the nearshore ecosystem, (3) explanation of the *change or action* to nearshore ecosystem structure or processes, and (4) predictions of the ecosystem *responses*. The submodel is then expressed as a map of interactions among the restored processes, the structural changes, the associated functional response, and the restoration action itself. Potential constraints are also identified as well as the associated uncertainty in the strength of interactions and in the accuracy of predictions.

Examples of Submodels

Examples of common submodels we have explored follow.

Dike Breach Scenario

One prominent change/action scenario involves breaching dikes that protect agricultural land from tidal inundation (Figure 7)—a restorative action intended to enhance juvenile salmon habitat.

Scenario: A historically diked wetland in an estuarine delta domain prevents or limits (depending on tide gate functionality) juvenile salmon rearing.

Change/action: Breaching or removal of dikes initiates the development of a tidal wetland and allows immediate fish access.

Predicted response: Opportunities increase for juvenile salmon to occupy shallow water habitat; capacity increases to support juvenile salmon foraging, which promotes increased residence time, growth potential, and refuge from predation.

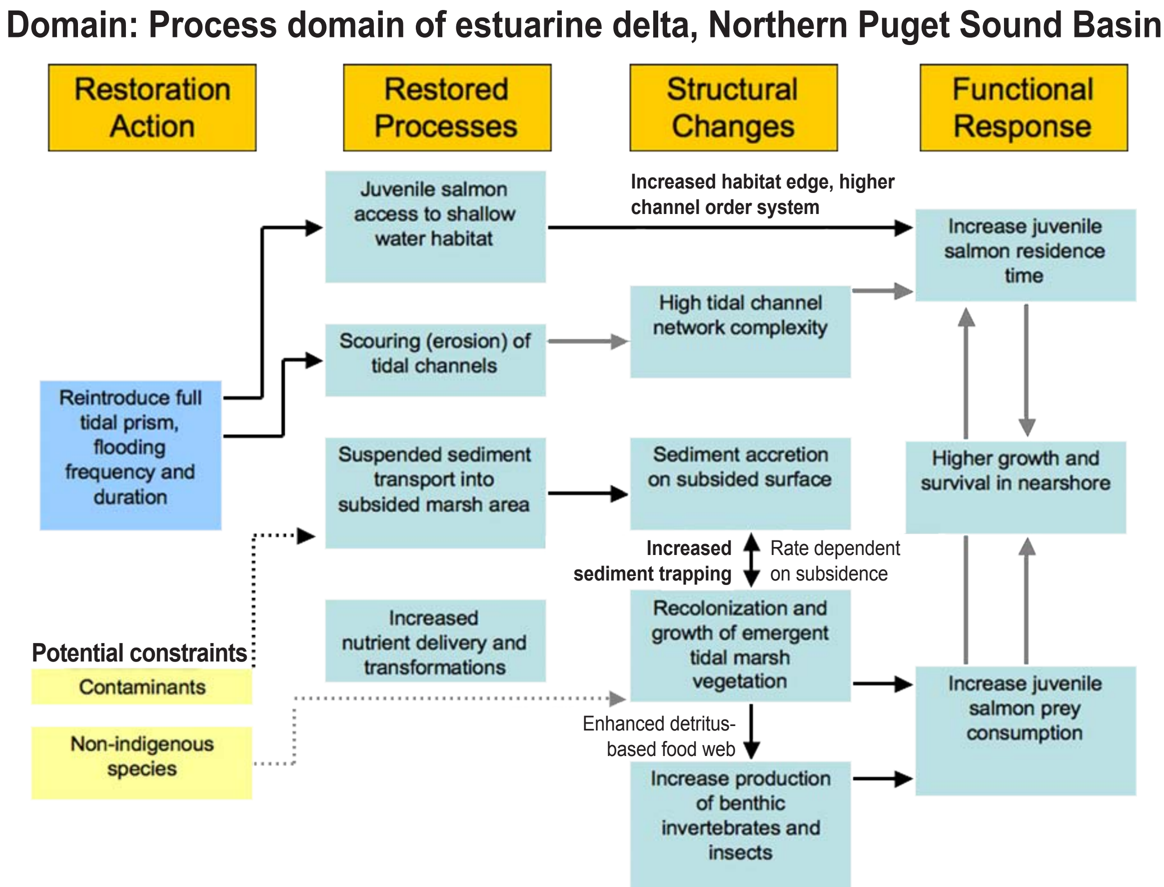


Figure 7. PSNERP–NST Conceptual Model Level 4 change/action scenario submodel illustrating example of breaching a dike in an estuarine delta wetland to restore full tidal inundation in support of juvenile salmon residence, growth, and refuge. The grey scale of arrows represents degrees of uncertainty, where black arrows represent relatively certain relationships and where light grey represents greater uncertainty.

Bulkhead Removal Scenario

Under some circumstances, shoreline armoring such as bulkheads can eliminate or modify nearshore ecosystem processes that delivery sediments from adjoining bluffs to the beach. In addition, they may also be associated with additional modification of the upland immediately behind the armoring, including removal or replacement of native vegetation. The combination of modified (e.g., sediment starved) beach substrate composition in the upper intertidal area of the beach below the bulkhead and the loss of overwater vegetative structure and shading overhead may impact spawning and empryo survivability of forage fishes (Rice 2006).

Scenario: A bulkhead degrades or eliminates (depending on tidal elevation and beach position) spawning habitat of forage fishes (Figure 8)

Change/action: Removal of the bulkhead restores the sediment source, wave energy regime, and riparian vegetation.

Predicted response: Opportunities increase for forage fishes to successfully spawn at appropriate tidal elevations and on requisite sediment structures, and for eggs to survive owing to riparian shading and other influences (e.g., seepage) favorably affecting temperature.

Beach Nourishment Scenario

One alternative to restoration of the nearshore processes involved with delivery of sediments from adjacent bluffs backing beaches is to import sediment from another source and deposit on sections of the beach where nourishment is desired or that will be transported to other sediment-starved areas.

Scenario: A beach is starved of natural sediment supply by artificial modifications of the shoreline (Figure 9).

Change/action: Beach nourishment adds sediment to the system.

Predicted Response: Nourishment increases the volume of sediment on a segment of beach, raising the beach profile and shifting it waterward. The effect of nourishment on sediment composition depends on the size of material added.

In this example, a Puget Sound beach is cut off from natural sediment supply by artificial modifications of shoreline. The resulting sediment-starved beach may be subjected to chronic erosion (shoreline retreat), changes to beach profiles, progressive loss of

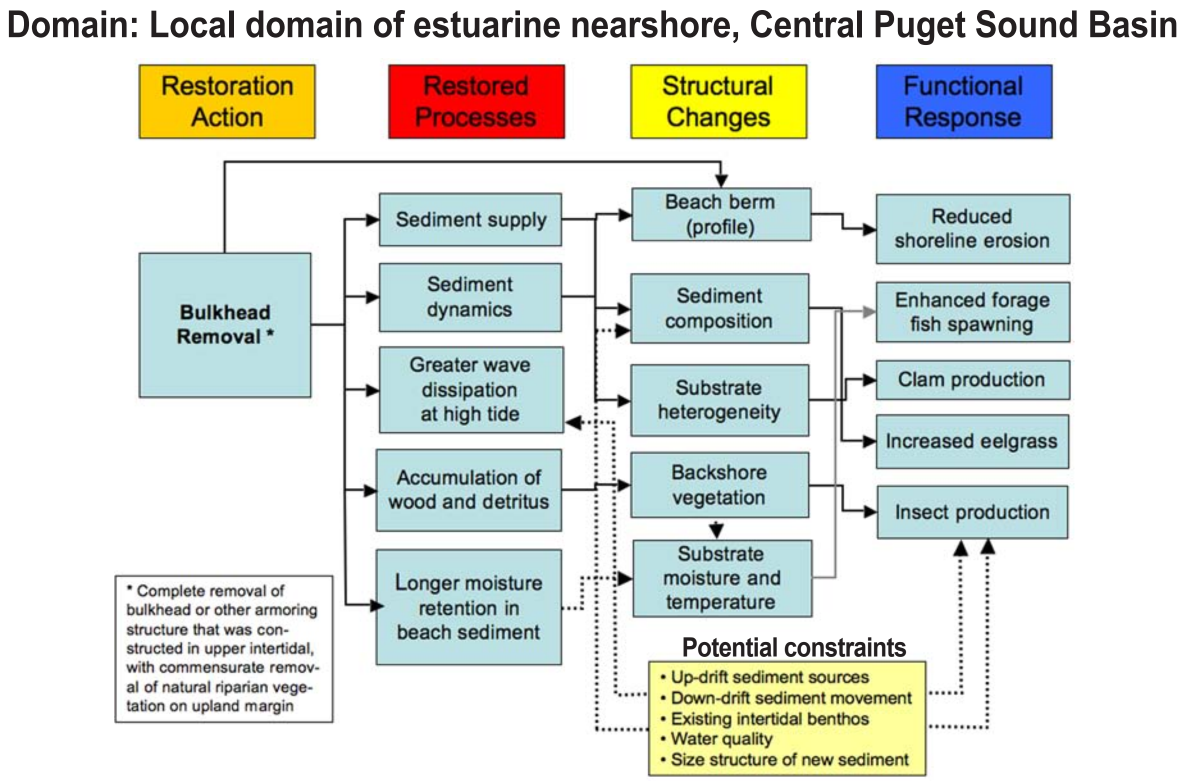


Figure 8. Level 4 change/action scenario submodel illustrating an example of a bulkhead removal along the estuarine shoreline to enhance forage fish spawning and eelgrass, clam, and insect production. (See Figure 7 for legend.)

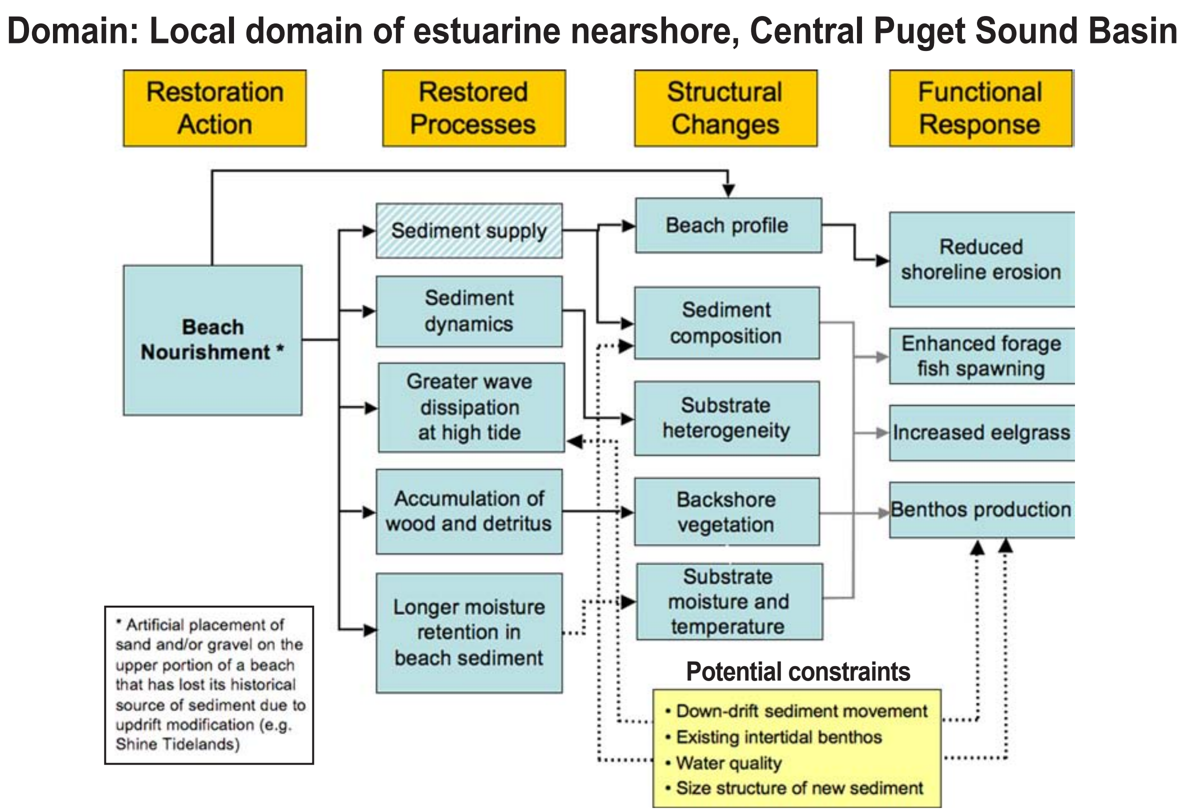


Figure 9. PSNERP–NST Level 4 change/action scenario submodel illustrating example of beach nourishment along estuarine nearshore beach to reduce erosion and enhance forage fish spawning, eelgrass and benthos production. (See Figure 7 for legend.)

upper portions of the profile (backshore and upper intertidal), and shifts in dominant sediment size (usually coarsening). Loss of berm width reduces the capacity of the beach to accumulate logs and debris and limits the establishment of backshore vegetation.

The suggested restoration action in this scenario is beach nourishment, which generally refers to depositing sand or gravel or both, usually from an external source, to the beach face (Figure 9).

As a result of beach nourishment, the volume of sediment on a segment of beach increases, raising the profile and shifting it toward the water. This typically results in upper intertidal and backshore zones expanding or reestablishing where they have been completely lost. The modified profile alters the way in which waves interact with the beach at higher tides and may change the dynamics of sediment movement during storms. Enhancing the berm allows more drift logs and detritus to accumulate and may also reduce erosion rates for upland areas behind the beach.

The effect of nourishment on sediment composition depends on the size of material added. Where nourishment consists of mixed sand and gravel, it often reintroduces sand to a beach that may be have become dominated by more coarse material (gravel, cobble). Even where nourishment consists of uniform gravel , it appears that this increases the ability to recruit and retain naturally available, sandier material. Nourishment generally results in greater heterogeneity of beach sediment, although it may also reduce the extent of a different, underlying substrate, such as "hardpan," that may have been exposed by previous erosion). The presence of a thicker veneer of beach sediment along with increased finer sediment may result in increased moisture retention within the sediments.

The expansion of the upper beach and the increase in fine gravel or sand may enhance the beach's suitability for forage fish spawning. In addition, modified wave interactions in this upper intertidal zone may have subtle effects on sediment deposition and erosion patterns that influence the successful deposition and development of eggs. The amount of wood and organic material on the berm likely would increase, resulting in enhancements in physical complexity of the high-tide beach, herbaceous vegetation, and detritus production and decomposition; this material also may effect a biotic response of increased diversity and productivity of biota adapted to these berm communities, such as certain amphipods ("beach hoppers"). Increased backshore vegetation would also likely result from input of seed material and organic matter present in the detritus as well as the increased area available for colonization.

Experience indicates that gravel-sized material rarely moves offshore, but where nourishment is carried out with sandy material, increased sand may be deposited offshore during storms and seasonal wave regimes. Where shallow subtidal areas are limited in sand, adding sandy material may enhance the abundance and productivity of eelgrass—possibly at the expense of hard-bottom flora such as kelp.

A particularly important step in working through a scenario such as that for beach nourishment is to link it back to conditions that affect the timeframe and variability over which this action sustains the desirable ecosystem structure (see Level 5: Time Variability). In this case, because the action is not actually restoring the process that naturally sustains sediment input, the action will have a comparatively short lifespan. Ultimately, the conditions that characterized a stressed ecosystem would return. However, this submodel would allow understanding and estimating the critical parameters that dictate the lifespan of the action.

Nutrient Enrichment Scenario

Eutrophication driven by excess nutrients (principally nitrogen) can impact nearshore ecosystems either by driving in situ production within the nearshore zone or by the advection of low-quality water (e.g., low dissolved oxygen) into the nearshore zone. Nearshore ecosystems may also be the site of excessive nutrient inputs (e.g., leaking septic tanks) as well as a region of intensive nutrient recycling.

Scenario: Excessive loading of nitrogen allows for naturally nutrient-limited algal populations to overproduce. The resultant organic load or algal biomass leads to hypoxia (in water) and smothering (on sediments) (Figure 10).

Change/action: Reduction in nitrogen loading allows the natural productivity cycle to reestablish.

Predicted response: The abundance, health, and diversity of nearshore populations is not threatened by burial or low oxygen, and they return to a more natural state.

Non-Indigenous (Vegetation) Species Scenario

A number of non-indigenous (exotic) species that invade otherwise unaltered beaches and estuarine wetlands can significantly alter nearshore ecosystem processes.

Scenario: An unvegetated mudflat is colonized by non-indigenous *Spartina alterniflora* (Figure 11).

Change/action: Vegetation colonization of the mudflat ultimately creates a high marsh that alters invertebrate community composition, creates a more structurally complex habitat, increases sediment deposition and surface elevation, and diversifies primary productivity.

Predicted response: The capacity to support juvenile salmon and avifauna is altered. Direction and magnitude of alteration differ according to species.

Mapping Level 4 to Level 3

Ultimately we must use the more simplistic change/action scenario submodel structure and predicted relationships and responses to populate the conceptual framework of the Level-3 process model. The submodels and Conceptual Model represent very different levels of complexity and uncertainty. Submodels are incomplete because they don't represent all fluxes, transformation, and so forth that we intend to capture in the Level-3 model. At the same time, because submodels focus on more specific interactions among processes and components, uncertainty about the scenarios explored in the submodels is potentially

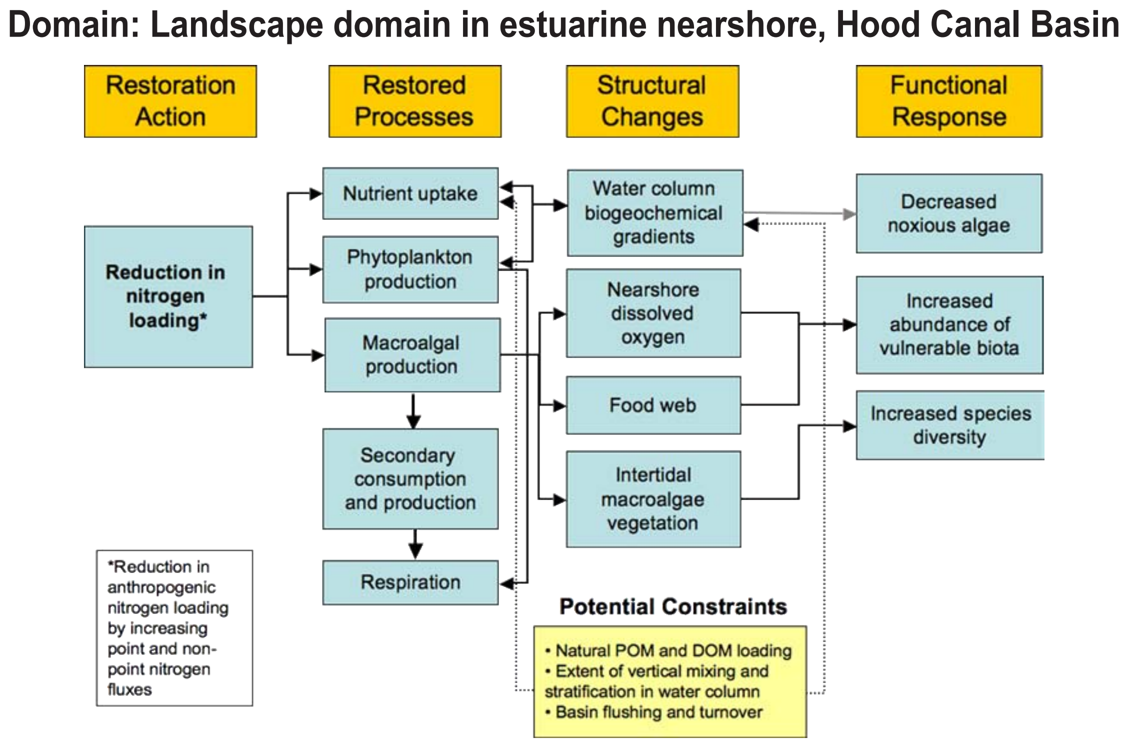


Figure 10. Level 4 change/action scenario submodel illustrating an example of the effects of landscape scale reduction of nitrogen loading in Hood Canal basin on natural processes and sensitive biota. (See Figure 7 for legend.)

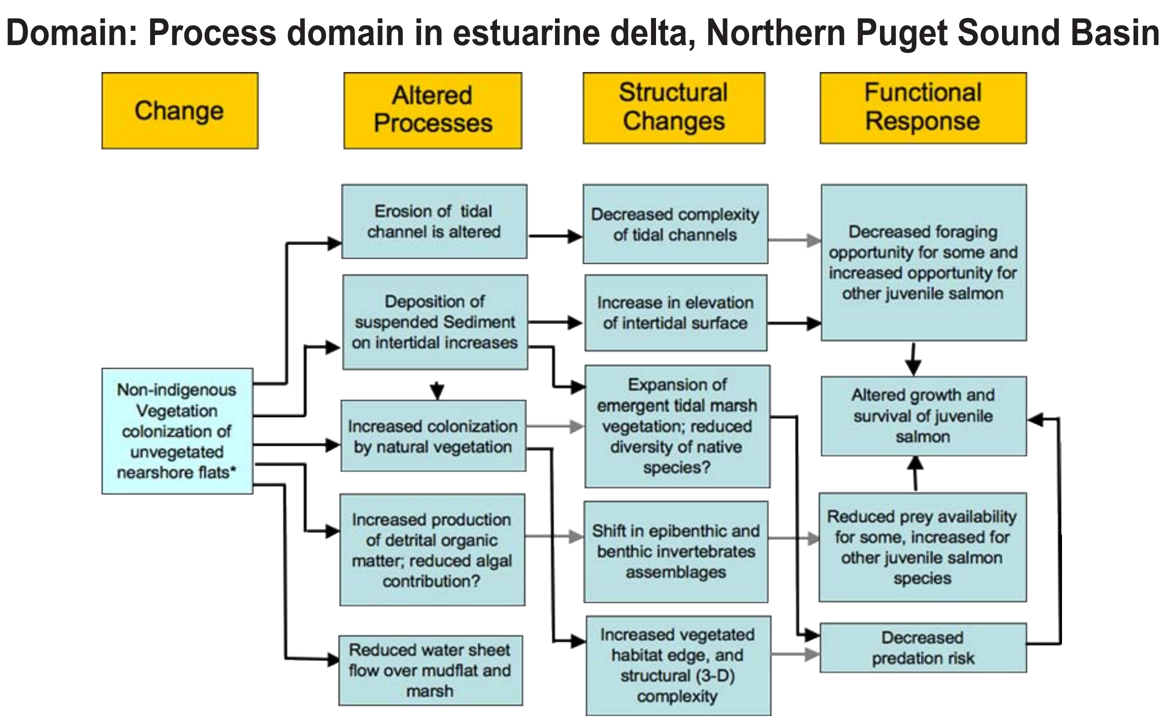


Figure 11. Level 4 change/action scenario submodel illustrating an example of changes imposed by the introduction of non-indigenous vegetation into process domain region of an estuarine delta in northern Puget Sound. (See Figure 7 for legend.).

greater. The challenge is to construct a fully connected conceptual model that accounts for all possible interactions and contingencies based on incomplete knowledge rife with the uncertainties and biases inherent in formulating the submodels.

Our approach to this challenge is to map objects associated with the Level-4 change/action scenario submodel (e.g., boxes under restored processes, structural changes, functional response) to structure or process "objects" in the Level-3 process model components (air, water, sediments, biology). Using the response "push" to a "receiver" object (i.e., pressure–state–response concept; Pieri et al. 1995), we can designate or identify the need for parameters (presence/absence, strength) or paths between objects (Figures 12 and 13). Completely populating a process model version for a change/action scenario submodel will be a major emphasis of the next phase of the PSNERP–NST Conceptual Model development.

Level 5: Time Variability

Time is an inherent variable in the NST Conceptual Model because ecosystem processes are dynamic and operate at different time scales, and because ecosystem responses to stressors and restoration actions do not occur over fixed timeframes. Cumulative impacts, irreversible changes in key processes, and the effects of disturbance events require an understanding of the space–time horizon over which stressors operate.

Similarly, the space–time horizons of restoration actions vary as a function of the ecosystem processes and structures involved. This requires comparing the time and space scales necessary to effect change and achieve desired responses. In Level 4, we assumed that the time over which altered nearshore processes operated and structural changes occurred would be integrated over the broad timeline dictated by the scenario. Level 5 demonstrates the need to consider the space–time variability required to assess ecosystem change generated either by natural processes or in response to a stressor or restoration action.

To represent the temporal and spatial scales over which change/action scenarios are predicted to persist, we modified a Delcourt (Delcourt et al. 1983) diagram (Figure 15). For example, the beach nourishment change/action scenario (see Level 4, Figure 9) can be illustrated as a localized imitation of natural processes, which dissipates over a somewhat broader spatial scale but comparatively short lifespan (without continued intervention of additional beach nourishment) (Figure 15a). In this example, the redistribution and lifespan of the deposited material will depend on local and process domain factors such as fetch and associated wave energy. In comparison, reintroducing natural sediment from an upland feeder bluff to a beach through the bulkhead removal scenario will not provide the same instantaneous source of sediment as in the beach nourishment scenario, but it will persist unaltered over a much longer lifespan and influence sediment accretion over a broader area, if it is not re-armored. Relative to

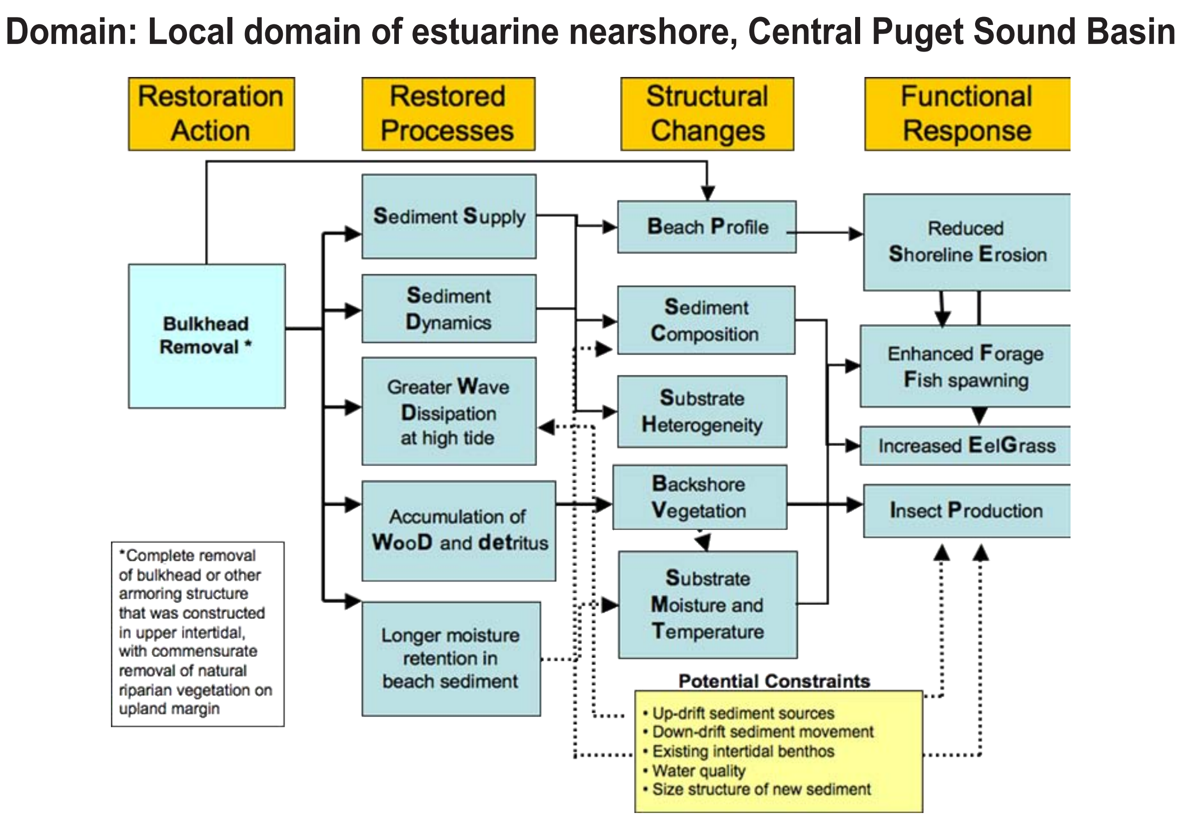


Figure 12. Repeat of Level-4 change/action scenario submodel shown in Figure 8, illustrating an example of a bulkhead removal along the estuarine shoreline to enhance forage fish spawning and eelgrass production. Bold letters indicate convention for mapping this submodel change/action scenario into Conceptual Model Level 3 (process), as illustrated in Figure 13.

Level 3—Submodel/Model Mapping

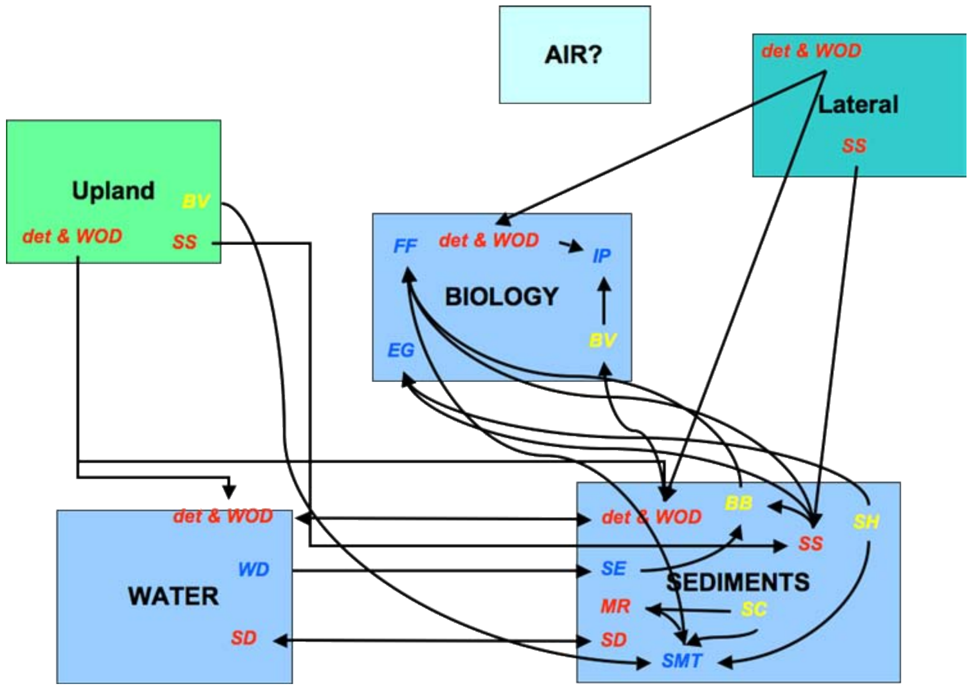


Figure 13. Example of mapping a Level-4 change/action scenario submodel (bulkhead removal) into Level-3 (process domain), representing a nearshore beach without a bulkhead. (See Figure 12 for abbreviation definitions.)

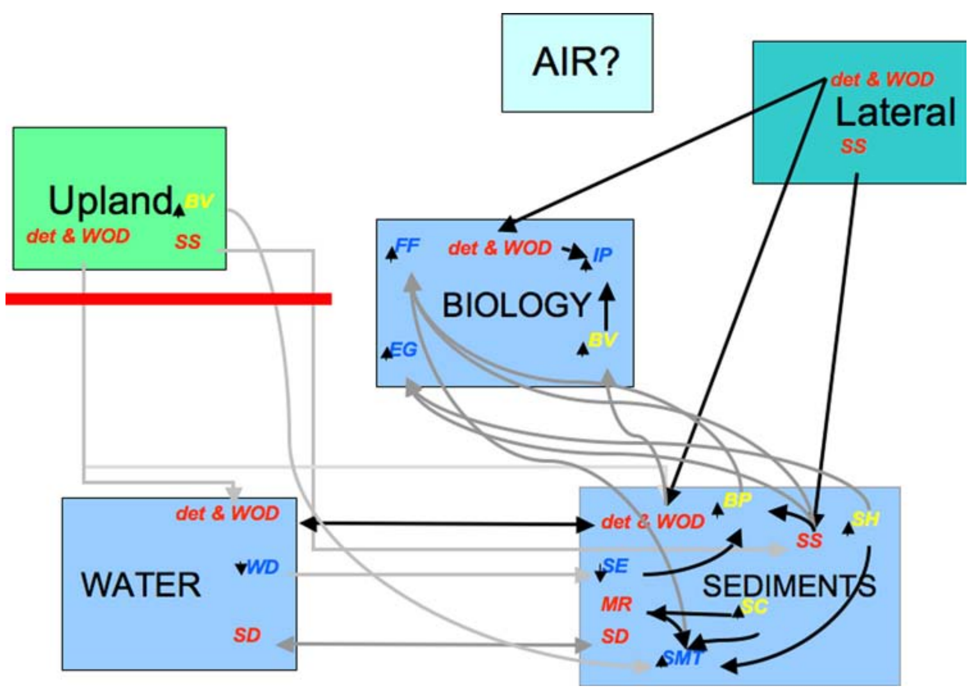


Figure 14. Example of mapping a Level-4 change/action scenario submodel (bulkhead removal) into Level 3 (process domain), where the effect of an anthropogenic stressor (bulkhead = red bar) is indicated as lost (light gray) or decreased (dark gray) process links to ecosystem components among upland, sediments, and biology. (See Figure 12 for abbreviation defintions.)

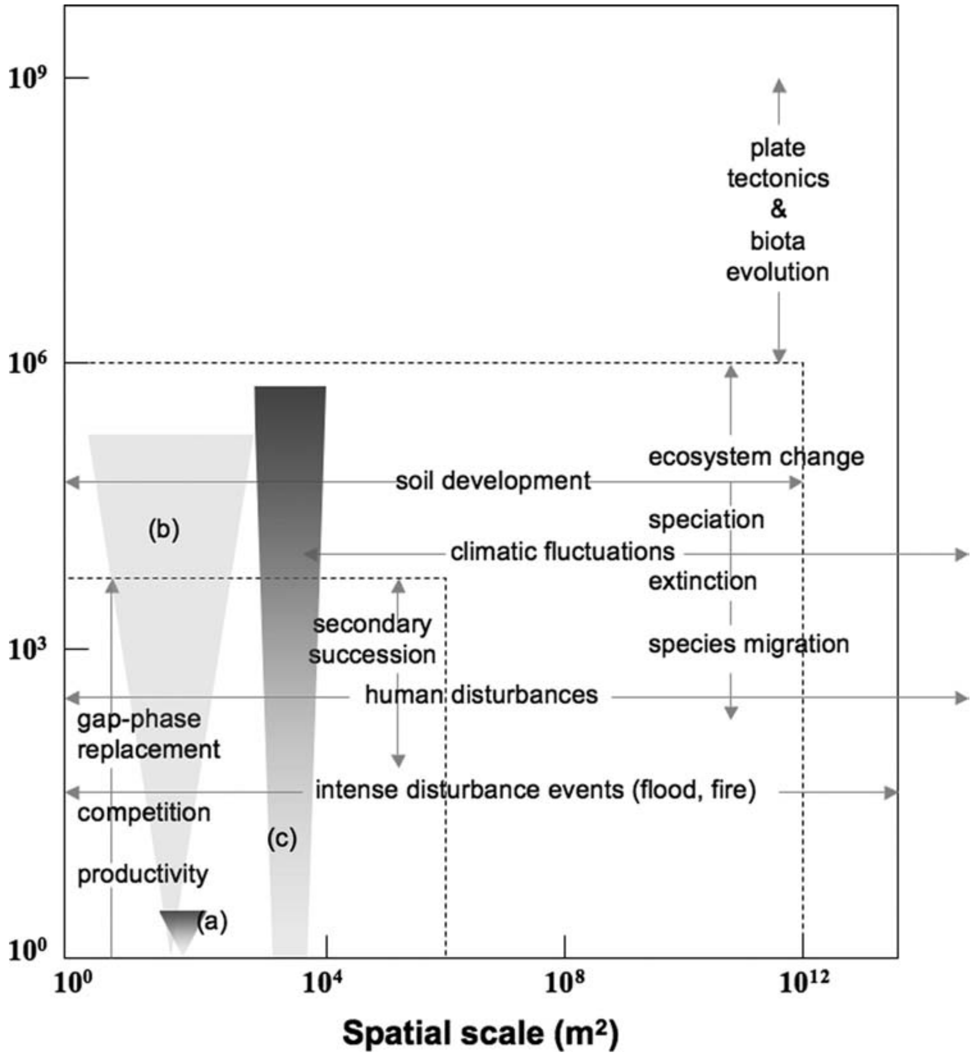


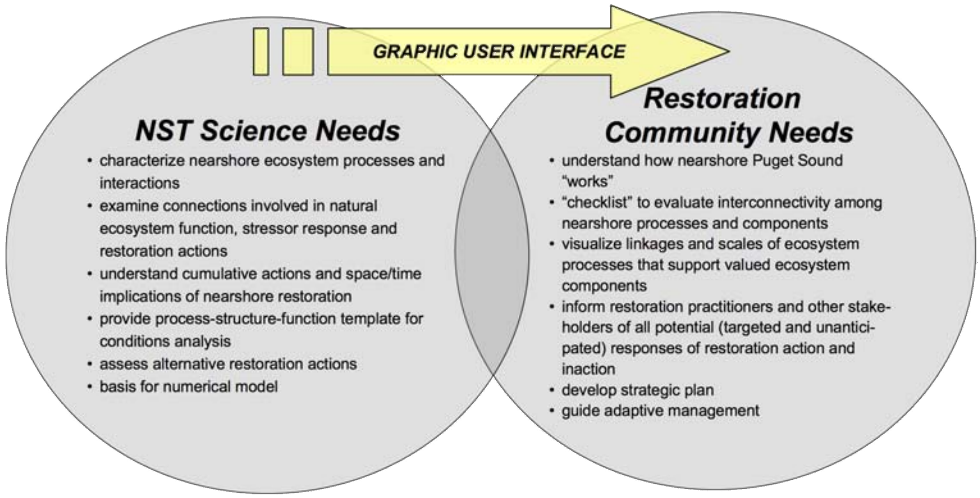
Figure 15. Relationship between spatial scale and temporal scale for natural and ecological processes affecting ecosystem change and restoration. Three scenarios are illustrated over the varying space and time durations of these changes and actions: (a) beach nourishment, (b) bulkhead removal, and (c) dike breach. (Modified from Delcourt et al. 1983).

beach nourishment, these sedimentation processes will not only be resilient to disturbance events but will increase during storm events.

The dike breach change/action scenario illustrates the different scales at which many of the nearshore ecosystem processes will be initiated immediately over a large spatial scale (Figure 15c). For example, the development of the wetlands over the newly inundated site will proceed for tens if not hundreds of years and the spatial area influenced will expand slowly beyond the tidally inundated area as the wetland becomes more productive and adjacent ecosystems expand.

Model Application

Although the development of this Conceptual Model has been focused on ecological principles and scientific understanding, we have not ignored the potential applicability of such a model for conceptualizing, designing, and implementing restoration actions in nearshore regions of Puget Sound (Figure 16). We have explored preliminary designs of interactive, internet-based applications that would educate and inform restoration practitioners and managers who do not necessarily require access to the scientific expertise behind the model's structure and operation. Such a graphical interface could be designed to allow participants with any expertise level to explore alternative applications of the Conceptual Model via an "interview process" that allows the operator to choose from various levels of detail or questions they wish to address (Figure 17). Appendix A presents an example sequence of such an Internet-based graphic interface. Further development of the Conceptual Model in such a "tool box" format will occur under separate Nearshore Partnership initiatives.



1. Identify elements of domain and stressors of concern
2. Establish:
   - Scope of action
   - Desired outcome
   - Assumptions
   - Contingencies
3. Prescribe landscape setting and external influences
4. Set time duration (lifespan)
5. Define and map nearshore components
6. Evaluate presence/absence, magnitude, and relative strength of internal and cross-nearshore processes
7. Assess longevity of processes, constraints, and sensitivity of assumptions (uncertainty)

Figure 16. Illustration of how science-based development of Conceptual Model by PSNERP NST could be translated through an internet-based graphical interface to meet the needs of restoration practitioners and other participants in the restoration community.

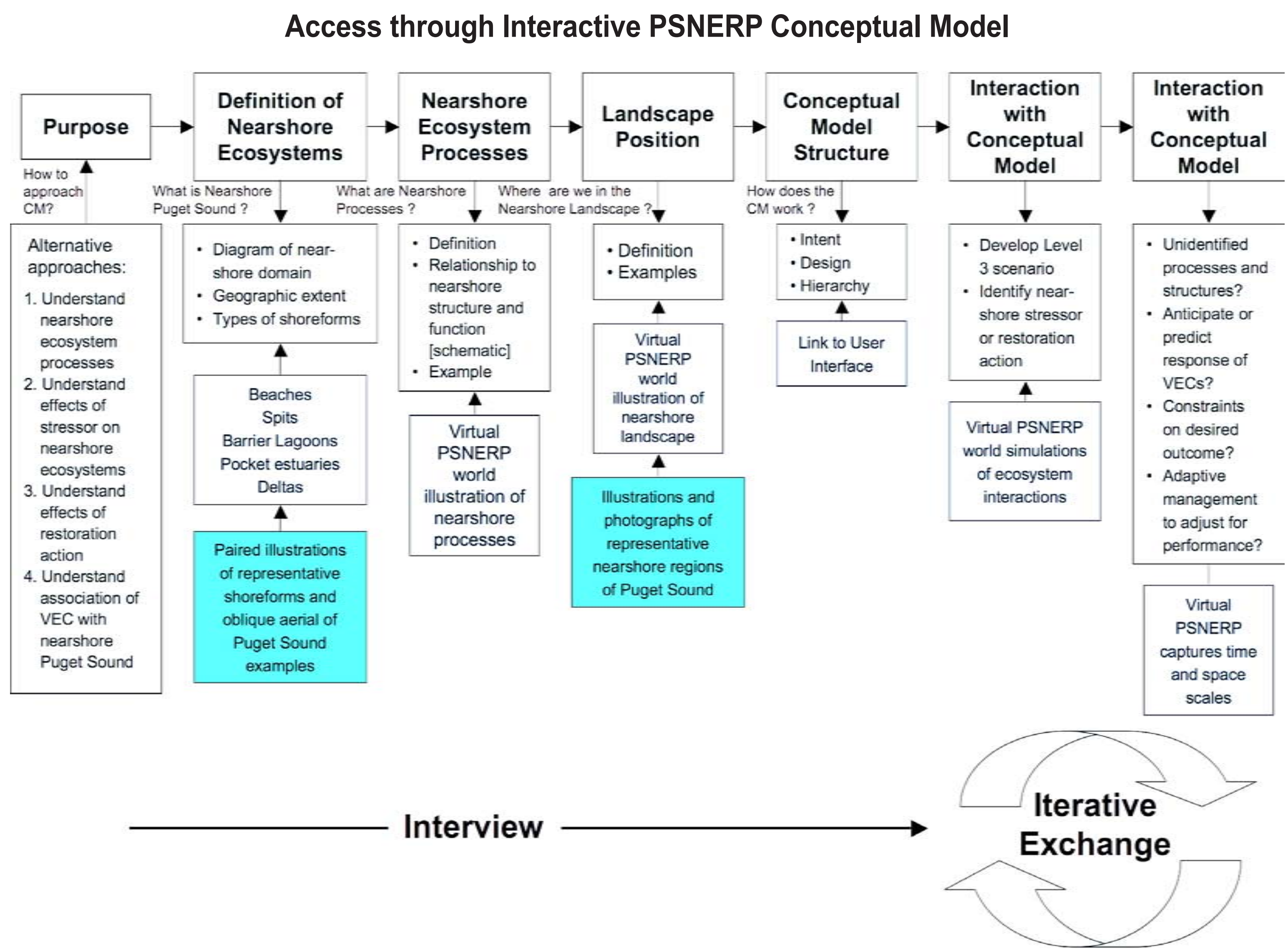


Figure 17. Example of the structure of an internet-based Conceptual Model that employs a graphical interface to enable a participant to explore various restoration interests or inquiries through sequential steps of an interview and iterative exchange.

References

Allen, T. F. H., and B. Starr. 1982. Hierarchy: Perspectives of Ecological Complexity. Univ. Chicago Press, Chicago. 237 p.

Benda, L., N. L. Poff, D. Miller, T. Dunne, G. Reeves, G. Pess, and M. Pollock. 2004. The network dynamics hypothesis: how channel networks structure riverine habitats. Bioscience 54:413-427.

Burns, R. 1985. The Shape & Form of Puget Sound. Washington Sea Grant Publication, University of Washington, Seattle, Washington. 100 p.

Delcourt, H. R., P. A. Delcourt, and T. Webb, III. 1983. Dynamic plant ecology: the spectrum of vegetational change in space and time. Quaternary Science Reviews 1:153-175.

de Wit, C. T. 1993. Philosophy and terminology. Pages 3-6 in P. A. Leffalaar (ed.), On Systems Analysis and Simulation of Ecological Processes. Kluwer Academic Publ., Boston.

Fresh, K., C. Simenstad, J. Brennan, M. Dethier, G. Gelfenbaum, F. Goetz, M. Logsdon, D. Myers, T. Mumford, J. Newton, H. Shipman, and C. Tanner. 2004. Guidance for protection and restoration of the nearshore ecosystems of Puget Sound. Puget Sound Nearshore Partnership Report No. 2004-02. Published by Washington Sea Grant Program, University of Washington, Seattle, Washington. Available at http://pugetsoundnearshore.org.

Goetz, F., C. Tanner, C. S. Simenstad, K. Fresh, T. Mumford, and M. Logsdon, 2004. Guiding restoration principles. Puget Sound Nearshore Partnership Report No. 2004-03. Published by Washington Sea Grant Program, University of Washington, Seattle,Washington. Available at http://pugetsoundnearshore.org.

Hobbie, J. E. (ed.). 2000. Estuarine Science: A Synthetic Approach to Research and Practice. Island Press, Washington, D.C. 539 p.

Huggett, R.J. 1993. Modelling the Human Impact on Nature: Systems Analysis of Environmental Problems. Oxford University Press, New York.

NRC (National Reserarch Council). 1990. Managing Troubled Waters: The Role of Marine Environmental Monitoring. National Research Council, National Academy Press, Washington D.C.

NRC (National Research Council). 1995. Review of EPA's Environmental Monitoring and Assessment Program: Overall Evaluation. National Academy Press, Washington, DC.

Newton, J., T. Mumford, J. Hohrmann, J. West, R. Llanso, H. Berry, and S. Redman. 2000. A conceptual model for environmental monitoring of a marine system. Puget Sound Ambient Monitoring Program. 12 p. plus appendices.

Pieri, C., J. Dumanski, A. Hamblin, and A. Young. 1995. Land quality indicators. World Bank Discussion Papers, No. 315. The World Bank, Washington, D.C.

Rice, C. A. 2006. Effects of shoreline modification on a northern Puget Sound beach: microclimate and embryo mortality in surf smelt (Hypomesus pretiosus). Estuaries and Coasts. 29:63-71.

Rosen, B. H., P. Adamus, and H. Lal. 1995. A conceptual model for the assessment of depressional wetlands in the prairie pothole region. Wetlands Ecology Management 3:195-208.

Shipman, H., M. Dethier, C. Simenstad, T. Mumford, and F. Goetz. In prep. Developing a geomorphic typology for the Puget Sound shoreline. Puget Sound Nearshore Ecosystem Restoration Project.

Simenstad, C. A., B. S. Miller, C. F. Nyblade, K. Thornburgh, and L. J. Bledsoe. 1979. Food web relationships of northern Puget Sound and the Strait of Juan de Fuca: A synthesis of the available knowledge. EPA DOC Research Report EPA 600/7 79 259 (also University of Washington, School of Fisheries, Fish. Res. Inst. FRI UW 7914, Seattle). 335 p.

Walters, C. J. 1986. Adaptive Management of Renewable Resources. MacMillan, New York.

Appendix A
Example of Interactive PSNERP Conceptual Model

The PSNERP "interactive" conceptual model is a suggested realization for the integration of ecology theory related to nearshore ecosystems, advanced visualization technology, and object orientated programming and dynamic model construction in the computer sciences. The following illustrations document the major aspects of a possible computer application or web-based interface designed to assist the user in both the exploration and investigation of Puget Sound Nearshore restoration.

The application interface is primarily designed as an interview with the user, requesting input and interaction while providing educational tools and illustrations of important ecological processes. The goal for such a model is to educate, inform, and assist the user in forming their own conceptual model as to how the complex interactions between ecosystem processes affect nearshore restoration outcomes. The model is not designed as an engineering tool or a site planning tool. Instead the model is designed as a planning tool which challenges the user to explore and explain their assumptions of nearshore processes across multiple spatial and temporal scales.

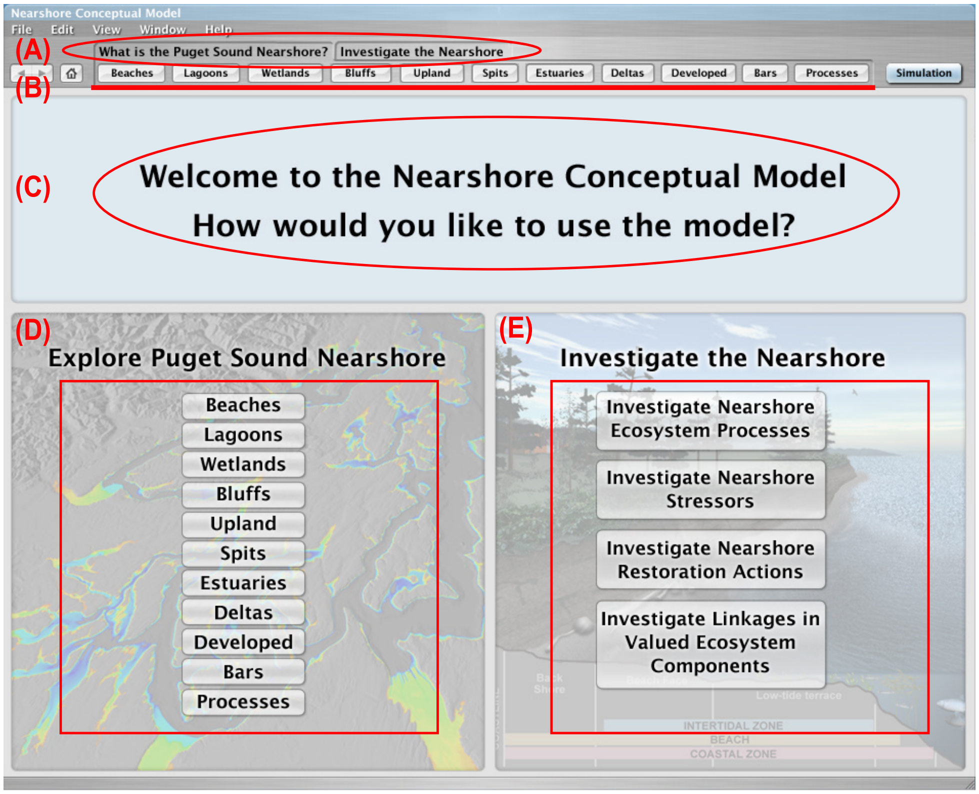


Figure A.1. Opening screen: The opening interface invites the users to select which of two modes (explore or investigate) to enter first. All subsequent interfaces follow the same layout of navigation menus: (a) Selection Mode for exploration or investigation, (b) Options Menu tabs, which are unique to each mode, (c) Section Title, (d) Option Dialogue window, and (e) Option Response window.

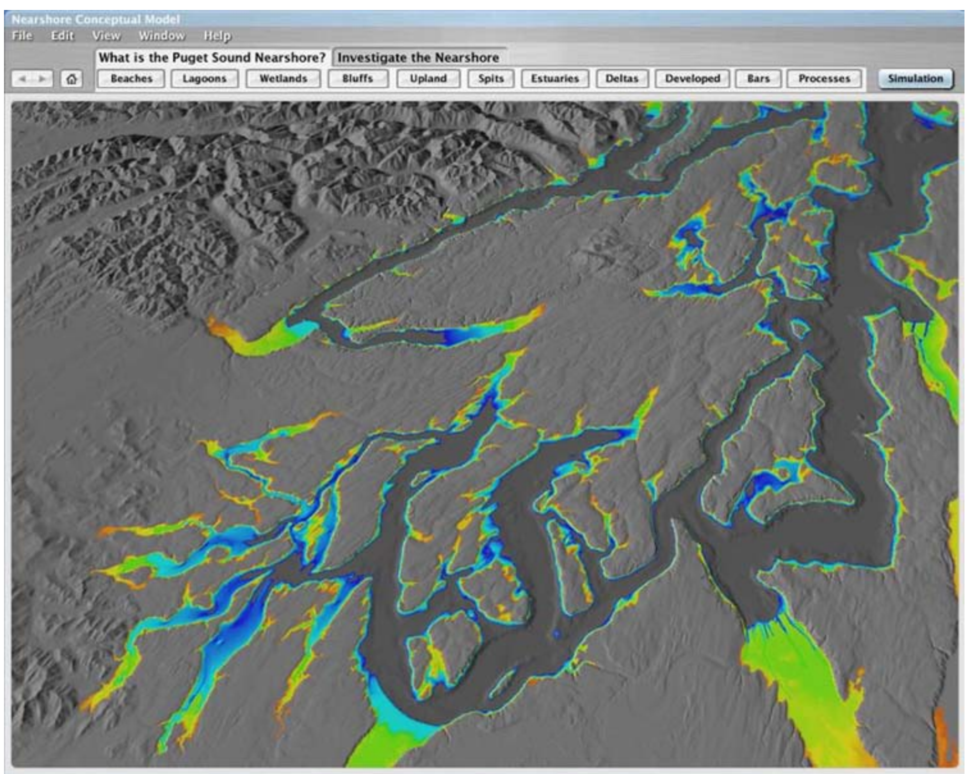


Figure A.2. Background template: In the exploration mode the user interacts with a geographic representation of Puget Sound. The background is a template that highlights the and tidally influenced, shallow water zone of Puget Sound.

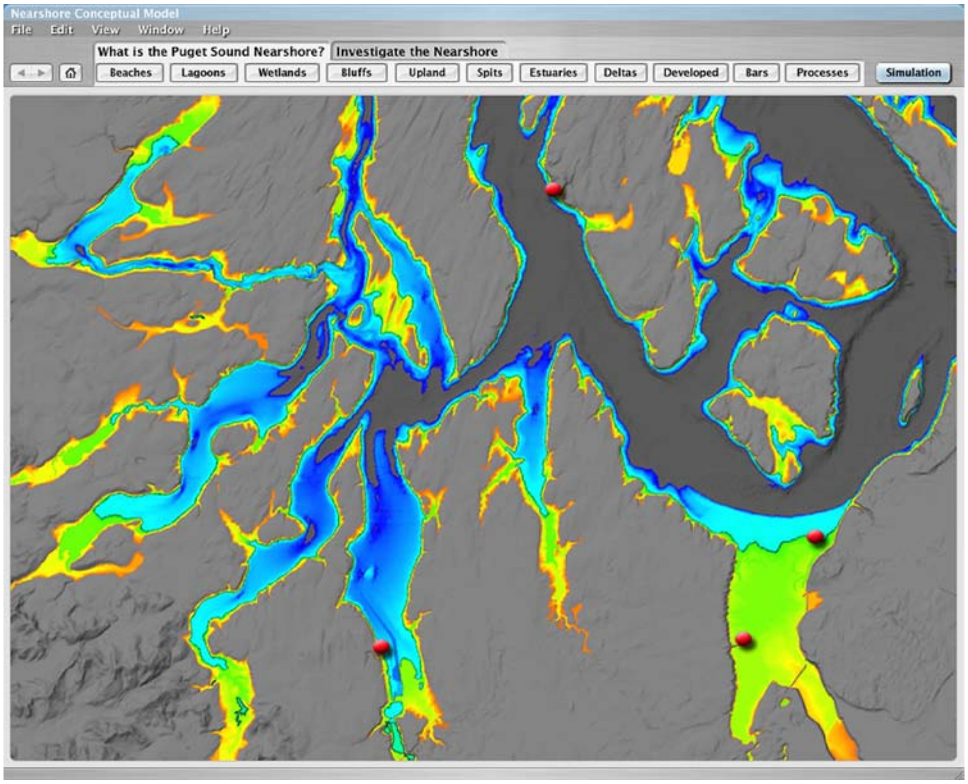


Figure A.3. Clickable pins: On the basis of the user's selection from the Option Menu tabs, clickable pins ("click pins") are displayed to illustrate the location of example nearshore landform units that may be selected ("clicked") to continue the user's exploration.

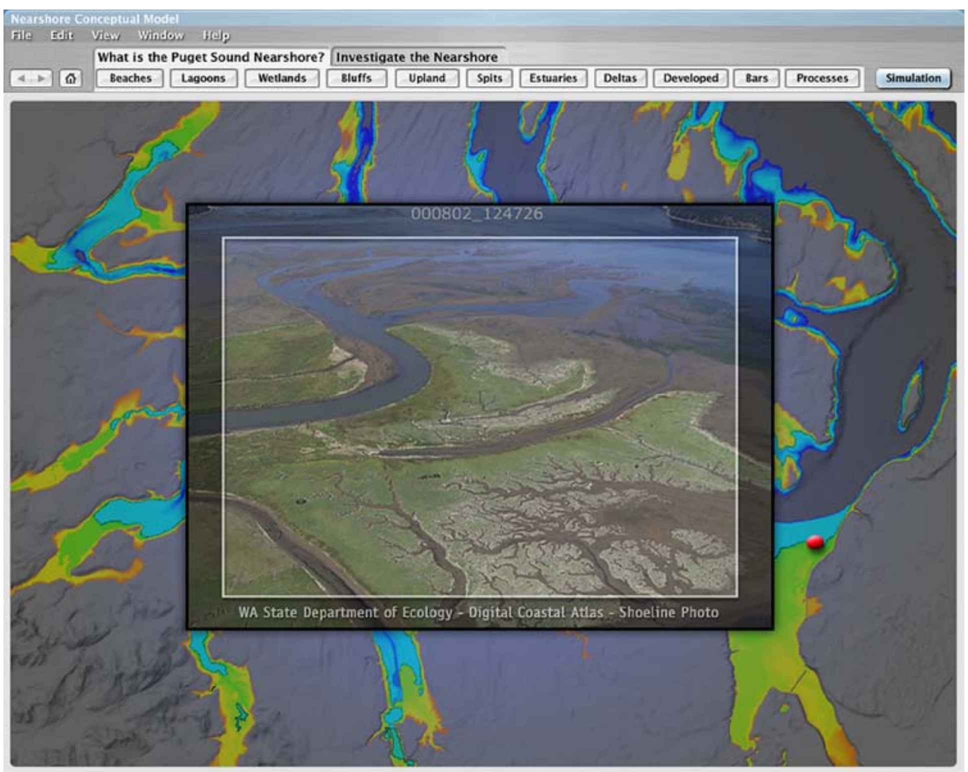


Figure A.4. Linked information: Click pins provide access to hyperlinked information such as digital aerial photography that resides in the program database and relates to that nearshore feature.

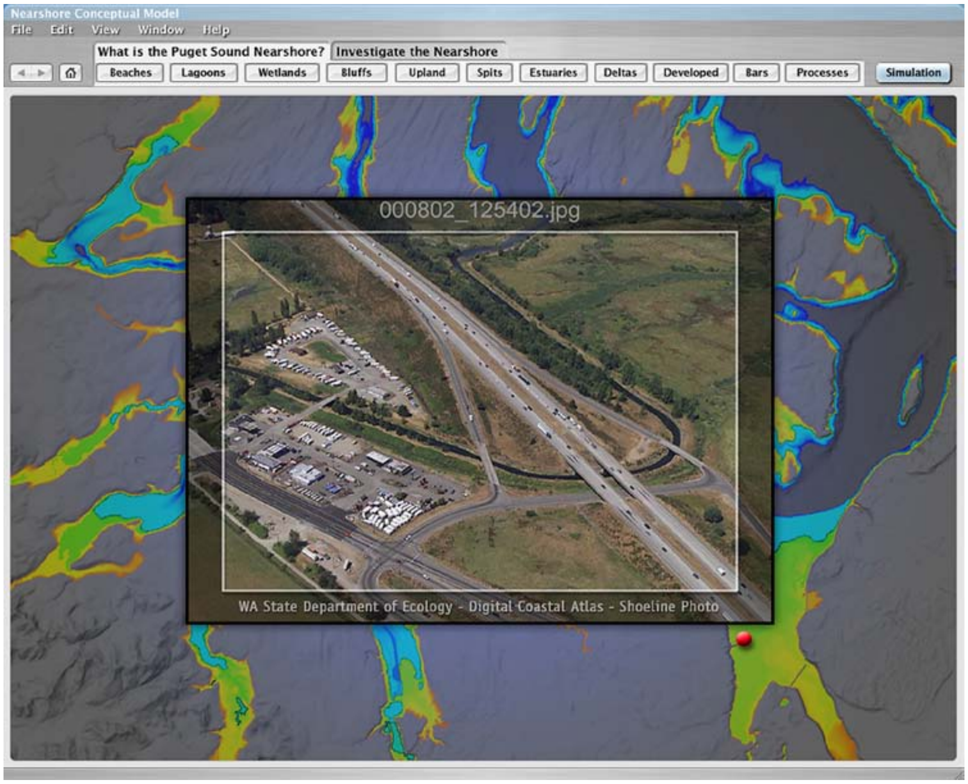


Figure A.5. Environmental setting: Click pins may present information that assists the user to recall or create a visual understanding of the surrounding environment.

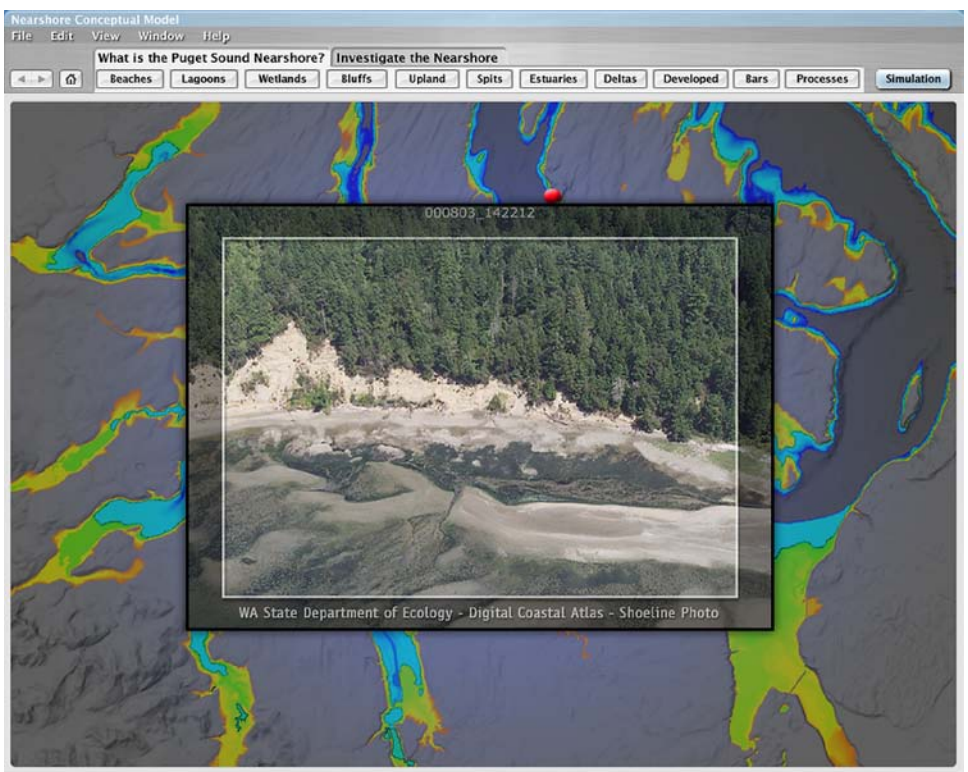


Figure A.6. Typical landform units: Many of the click pins will be used to illustrate typical nearshore landform units. Here the user has selected to explore bluffs.

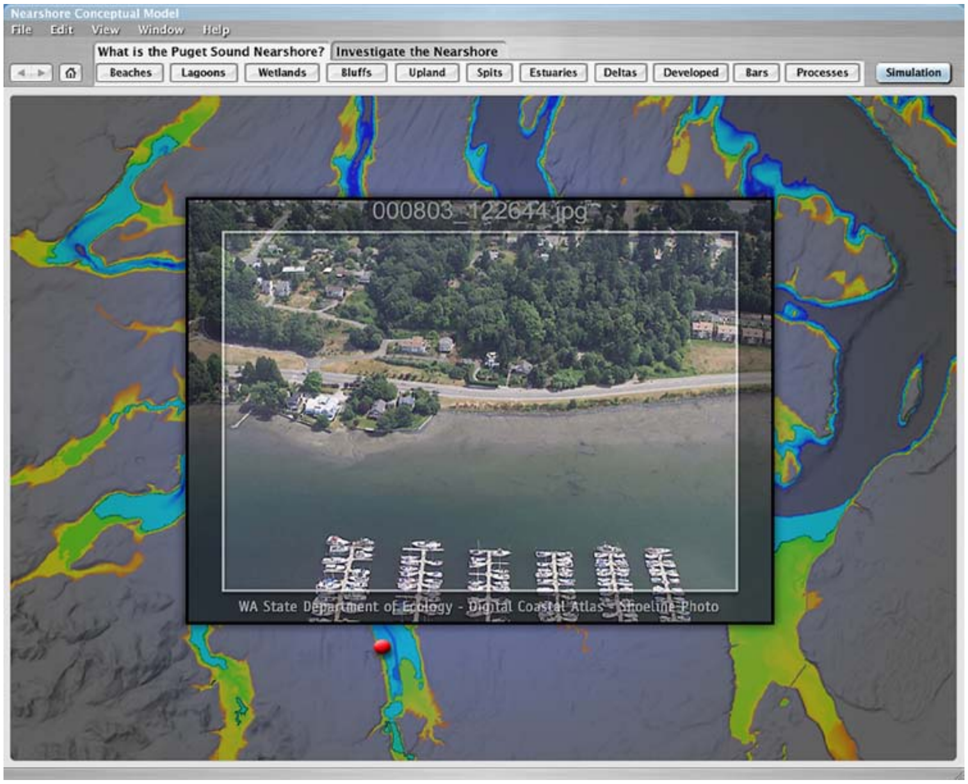


Figure A.7. Illustration of processes: In addition to landform units, many click pins may provide the opportunity to explore the interaction of ecosystem processes such as beach formation and erosion where alteration by various forms of ecosystem modification is present.

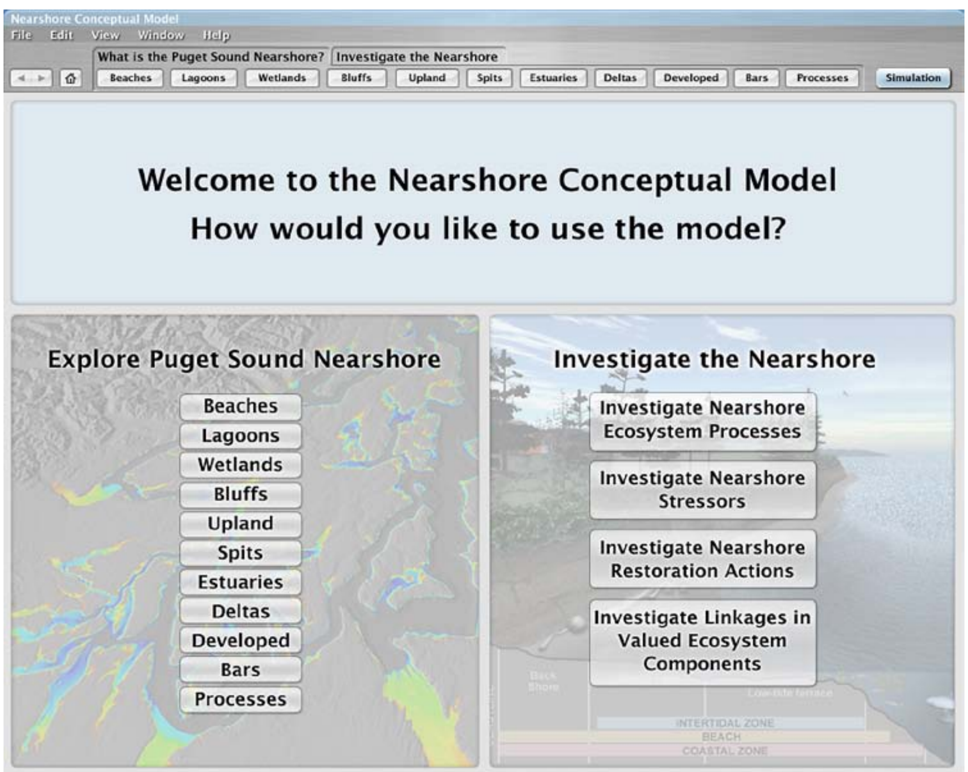


Figure A.8. Back to start: The user may return “HOME” to the opening interface at any time, creating an open format to the application and encouraging the user to switch between modes when they find it helpful.

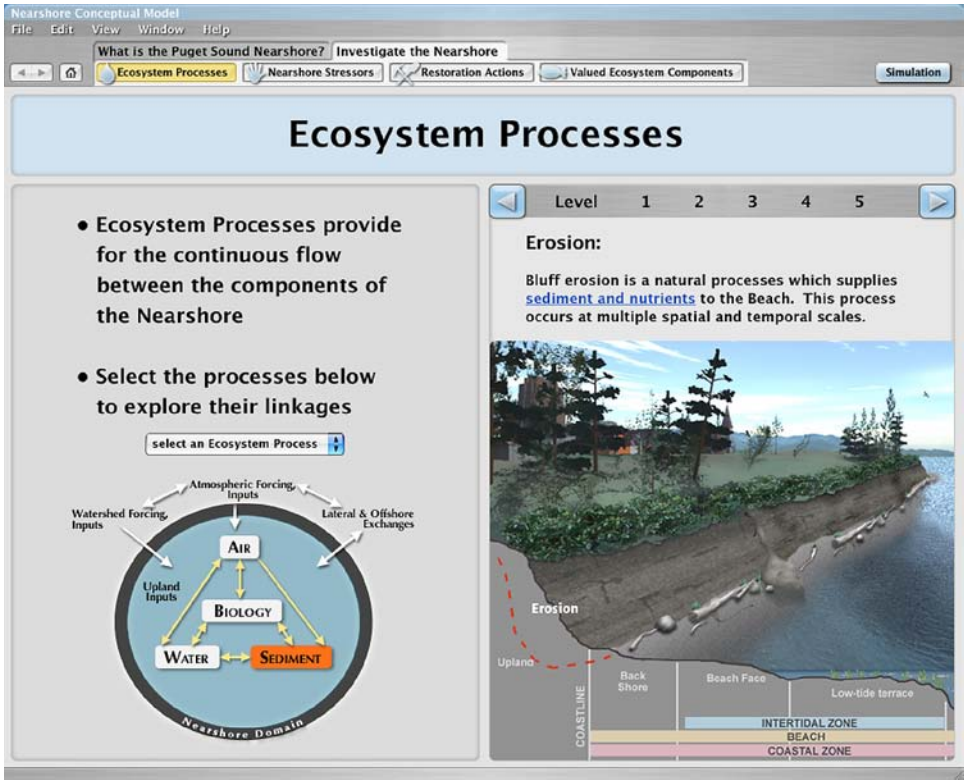


Figure A.9. Entering the investigation mode: In the investigation mode, the Option Menu tabs allow the user to select the option that best represents their approach or purpose for understanding the nearshore ecosystem. The user may select from four different "perspectives" for the use of a conceptual model of the nearshore (ecosystem processes, nearshore stressors, restoration actions, or valued ecosystem components). These perspectives are entry points into the same model but they represent the user's unique purpose or reason for undertaking this investigation. Here the user has entered through the "Ecosystem Processes" tab and both the Selection Dialogue window and the Selection Response window are set to LEVEL 1 of the underlying Conceptual Model building investigation. Selecting a process of interest highlights that process in a map of the conceptual model and opens a link to an informative response in the Selection Response window.

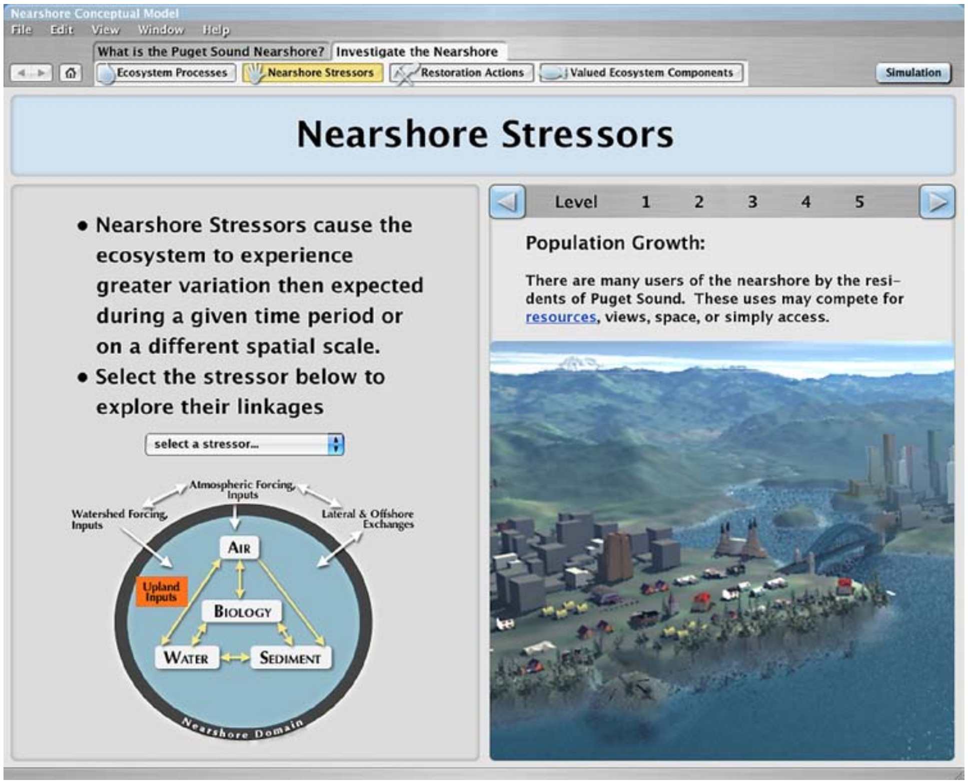


Figure A.10. Unique investigative tabs: Each Option Menu tab uniquely begins a LEVEL 1 interaction with the model. Here the user has chosen to investigate nearshore stressors.

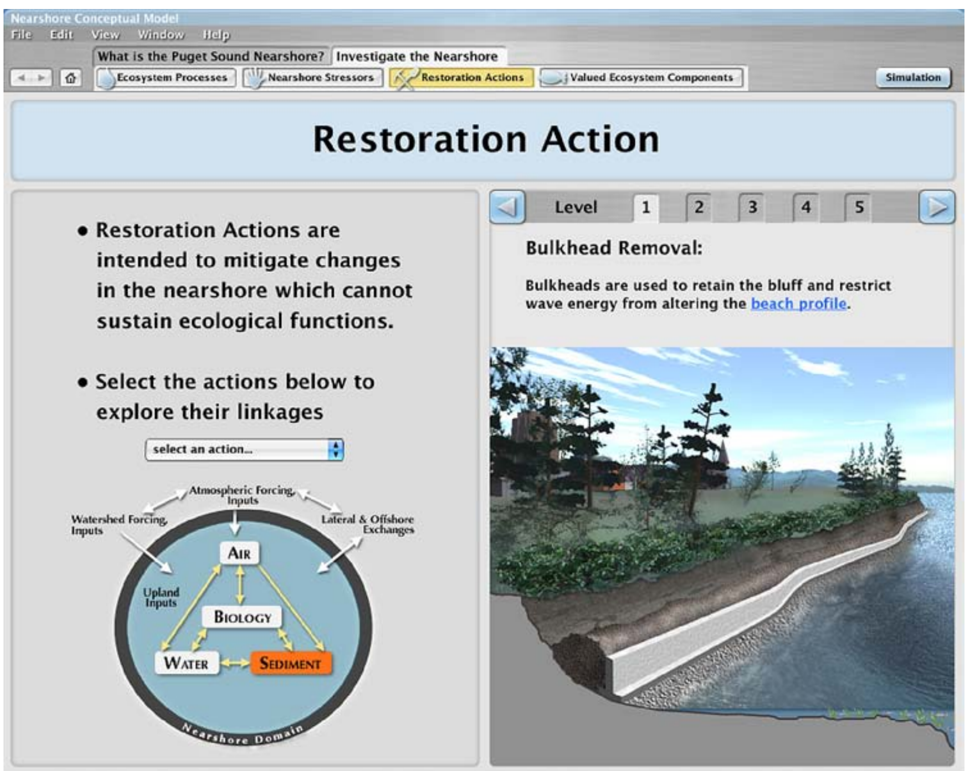


Figure A.11. Restoration Action: While all investigative options begin at LEVEL 1, the Restoration Actions tab illustrates the full use of the other levels of the interface. Here the user has chosen to investigate the Restoration Action of bulkhead removal.

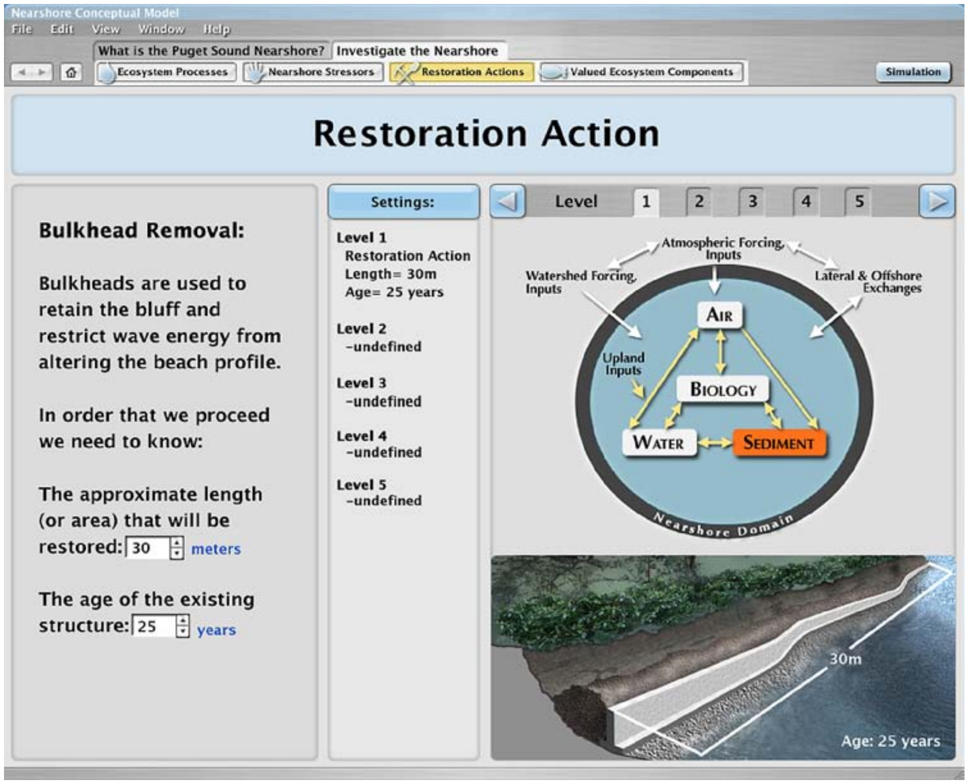


Figure A.12. LEVEL 1: To investigate other levels in the model, the user must initialize the spatial and temporal extent of the model. All user-defined settings are displayed in the Option Response window along with helpful illustrations or explanations.

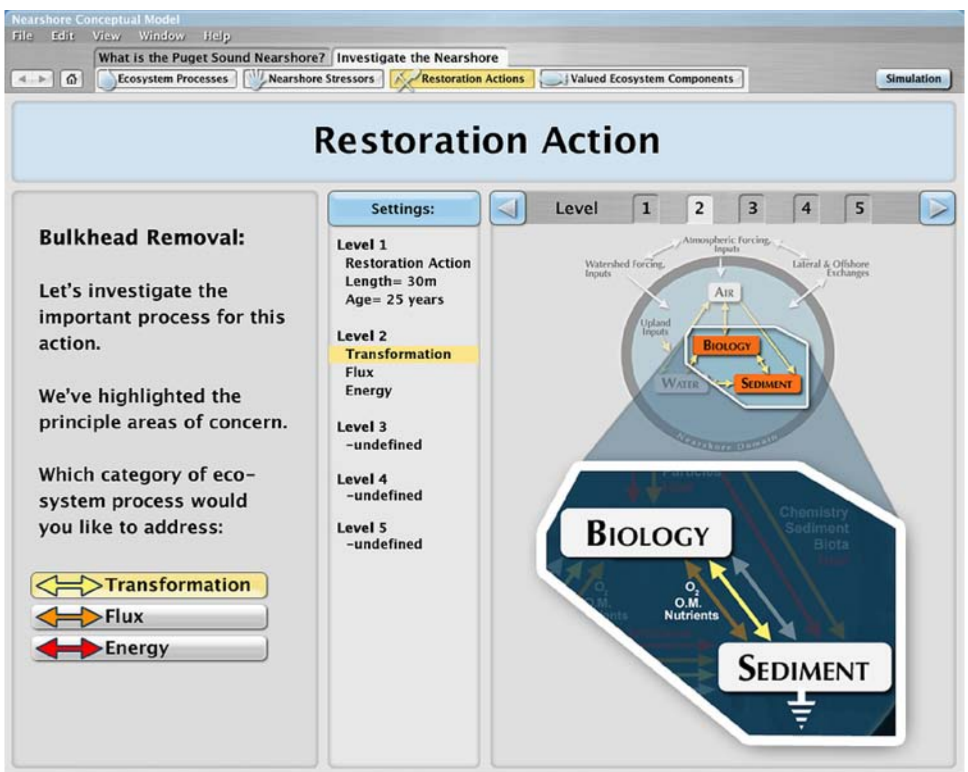


Figure A.13. LEVEL 2: At LEVEL 2, the user must address the process linkages between major components of the ecosystem. Here the user is informed that transformation linkages exist between the sediment and biology components of the conceptualized nearshore ecosystem.

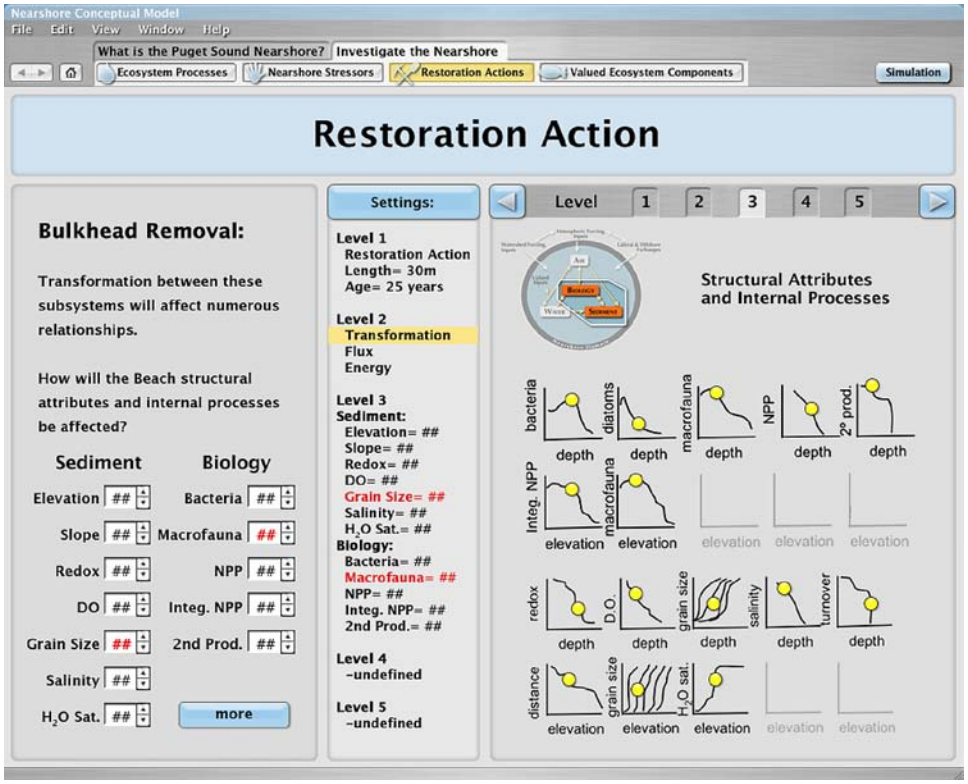


Figure A.14. LEVEL 3: At LEVEL 3, the user must explicitly state their understanding of their conceptual relationship between internal processes linking these components. As the user interactively increases or decreases the effect of each attribute of a component, the Option Response window charts the user's input and updates the current "settings." Some relationships are highlighted (red text) to ensure that the user selects something other then default settings.

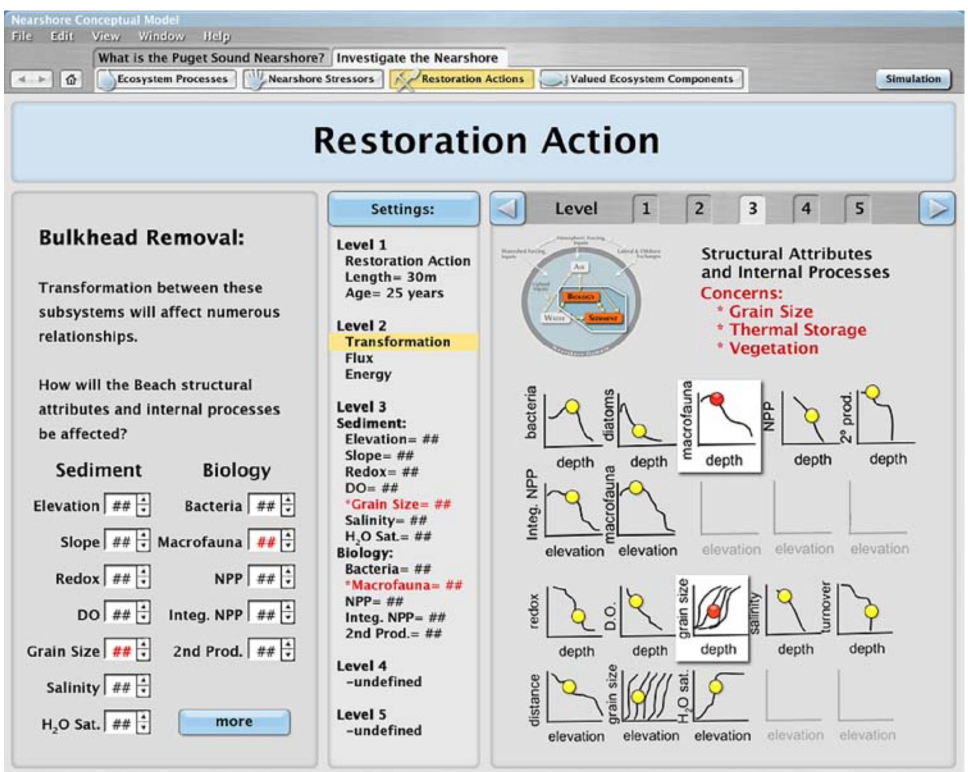


Figure A.15. Flagging responses: If the user input creates a charted relationship to fall outside a theoretical threshold as defined within the model, that relationship is flagged and the user is required to adjust their input.

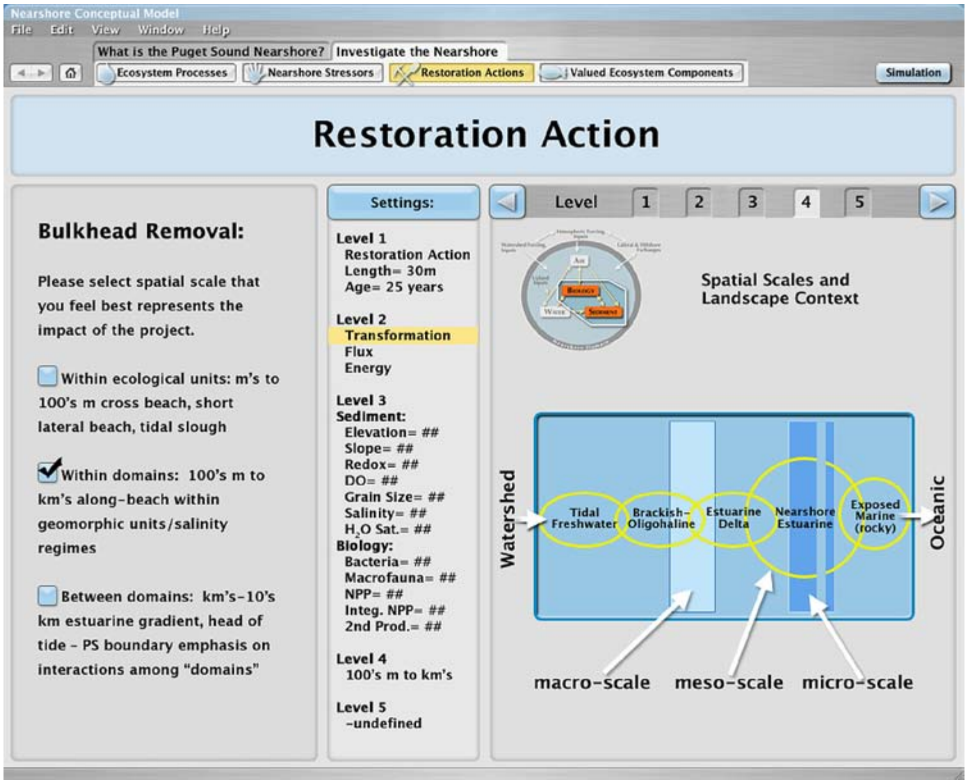


Figure A.16. LEVEL 4: At LEVEL 4, the user must address the spatial context or scale over which these processes are to interact with other nearshore landform units. This interface ensures that the user conceptualizes connections beyond the project boundary.

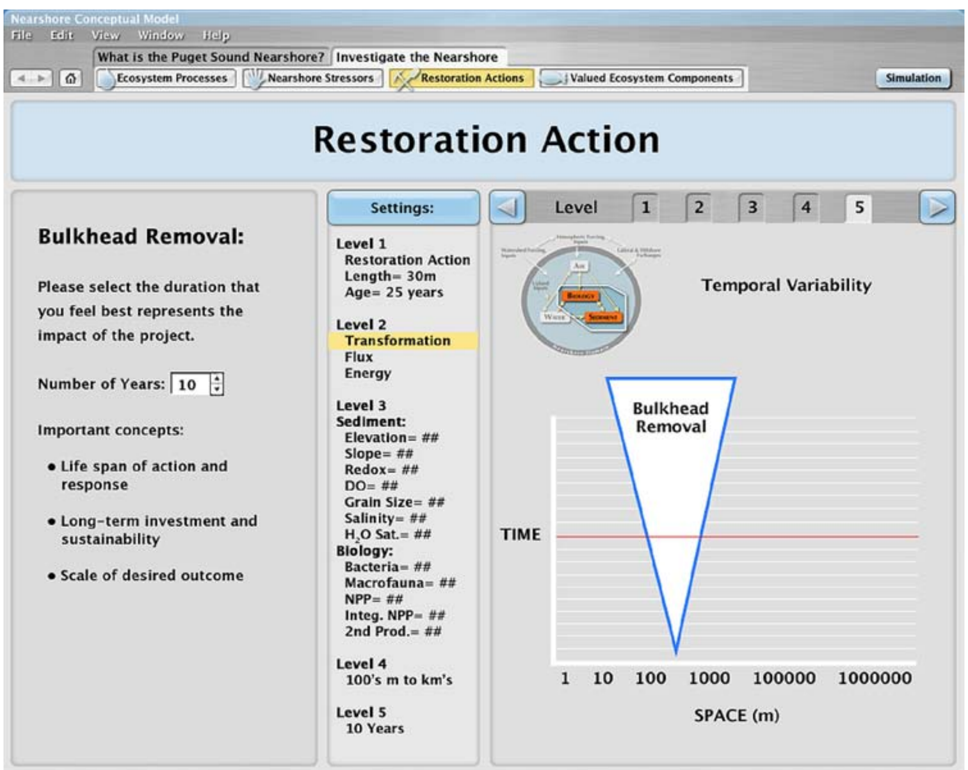


Figure A.17. LEVEL 5: At LEVEL 5, the user must address the length of time in which these processes are to "impact" the affected ecosystem. This interface ensures that the user conceptualizes connections beyond the length of time required for construction.

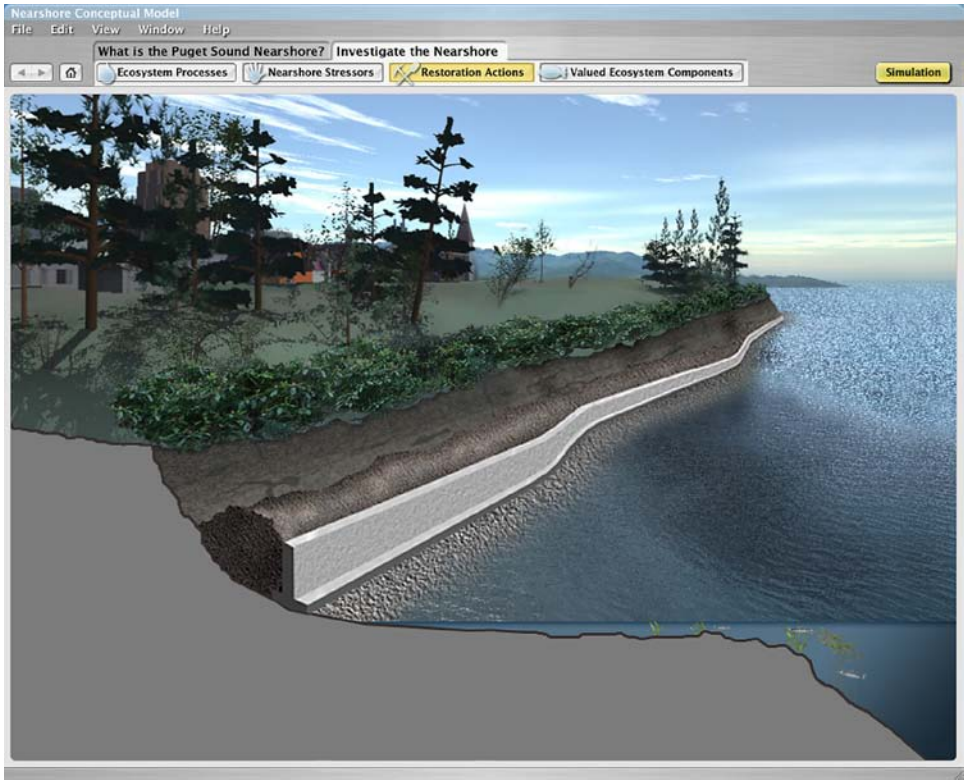


Figure A.18. Simulation: The final step is to view an animation that simulates these prescribed processes as they interact over space and time. Here the Simulation portrays a hypothetical nearshore segment and a bulkhead which will be removed based upon the user's defined settings established at all levels of the model.

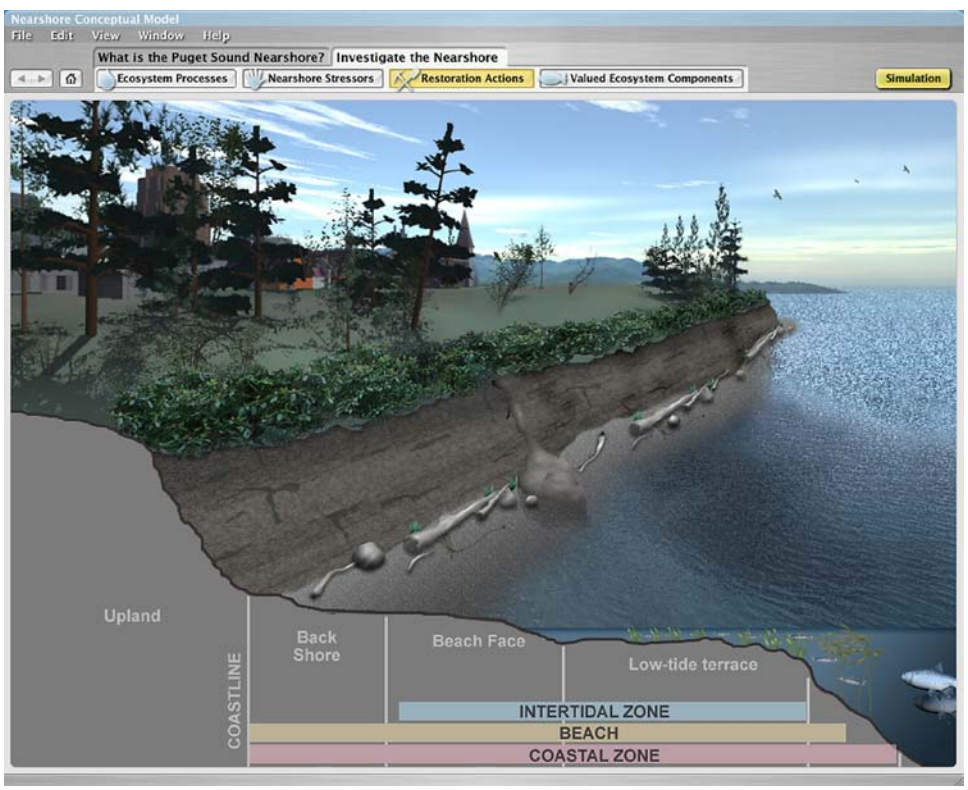


Figure A.19. Expected events: As the model animation simulates the removal of the bulkhead forward in time, the events which are expected to occur are displayed.

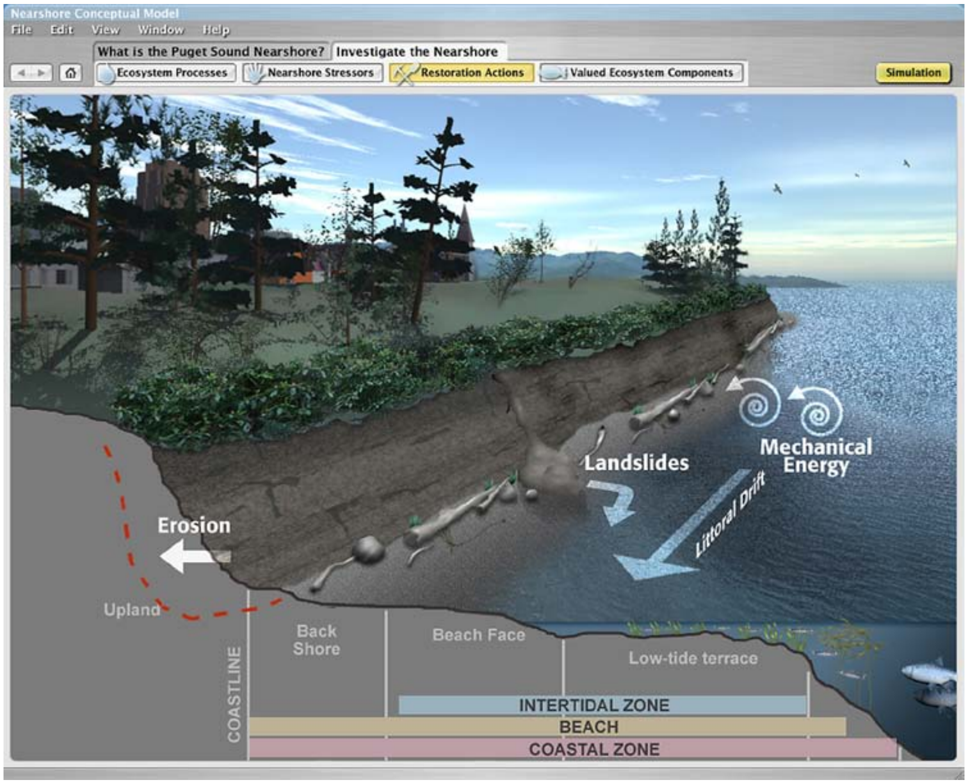


Figure A.20. Display of key processes: To assist the user in refining the attributes of affected processes in future model simulations, key processes used by the model during each simulation are displayed.

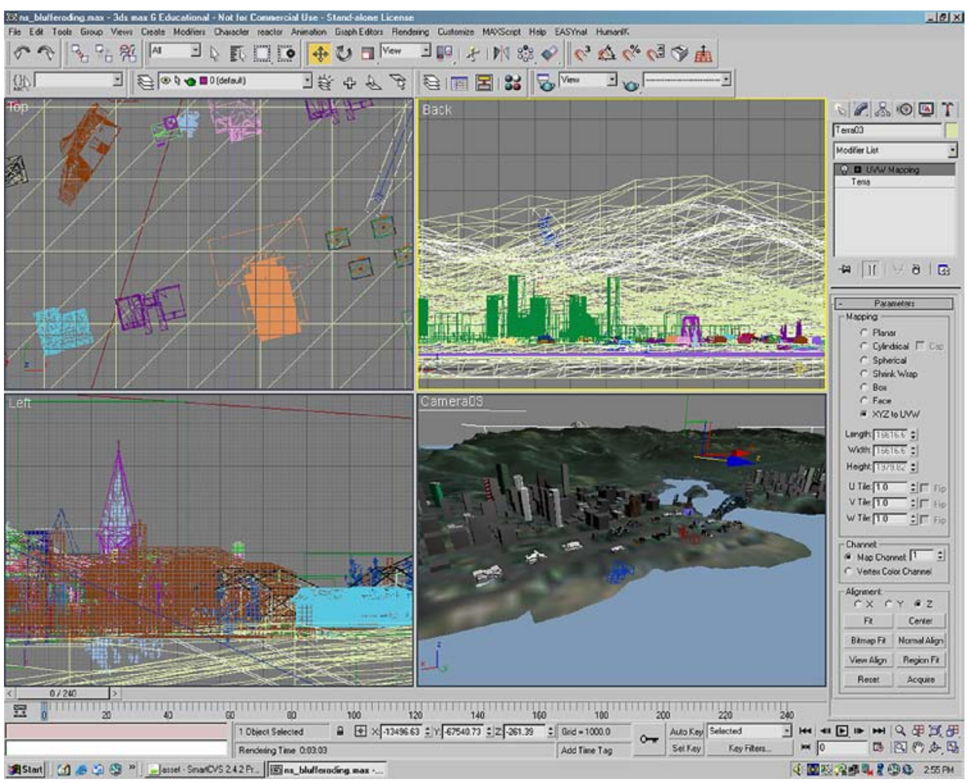


Figure A.21. Object database programming engine: The object-orientated programming elements used in these interactive, dynamic models are stored in an application database that describes the possible trajectory of each object based upon key relationships controlled by the user's input. The final animated simulation is therefore constructed as feedback to each unique setting defined by the user.

Appendix B
Conceptual Model Glossary

- *actions*: measures, including restoration or other physical alterations, as well as management and regulatory changes, that address the objective of recovering or improving nearshore ecosystem processes: the NST considers all of these to be management measures, inclusive of physical, policy, educational or other types of changes that are designed to improve the functioning of nearshore ecosystems
- *constraints*: external environmental stressors and other influences that could potentially constrain the effectiveness of restoration actions in nearshore ecosystems: For instance, contaminated sediments within or adjacent to a nearshore restoration site could alter both the ultimate effectiveness of improving the habitat value of restoration for nearshore organisms but also alter the feasibility and cost efficiency of the restoration action.
- *ecosystem*: a dynamic complex of plant, animal, and micro-organism communities and their non-living environment interacting as a functional unit: An ecosystem can be of any size-a log, pond, field, forest, or the earth's biosphere-depending upon the organisms that are the frame of reference, but it always functions as a whole unit. Ecosystems are commonly described according to the major type of vegetation, for example, forest ecosystem, old-growth ecosystem, or range ecosystem.
- *ecosystem functions, goods and services*: the diverse benefits that humans derive from natural ecosystems: they are usually categorized as regulation, habitat, production, and information functions.
- *ecosystem processes*: interactions among physiochemical and/or biological attributes of an ecosystem that involve changes in character of the ecosystem and its components: Processes are generally characterized as rates or patterns of change over time, and operate at various, hierarchical spatial and temporal scales. In the context of the PSNERP-NST Conceptual Model, ecosystem processes maintain and alter ecosystem structure and dynamics.
- *ecosystem structure*: physical and biological structure and organization of nearshore ecosystems: Ecosystem structure can be described at multiple scales—geomorphic organization of substrates and water bodies to vertical stratification of organisms by depth at a point in a beach—and at multiple dimensions—vertically in one dimension to 3-dimensions.
- *objects*: individual elements or components of a model for which explicit forms of interaction may be defined. Object-based modeling allows for consistent behavior by all modeling objects of the same type in the earlier levels of the conceptual model and unique behavior when spatial, temporal, or process specific conditions are defined. These behaviors may describe simulations such as movement or growth, or calculations such as absorption or chemical fixation. For the Conceptual Model, objects represent "fine scale" discrete elements of interest and concern to the user.
- *process-based restoration*: restoration and other management measures that target the recovery of natural nearshore ecosystem processes, as opposed to structural changes for instance
- *properties*: characteristics or attributes of an ecosystem, including both physicochemical and biological components
- *relationships*: associations between and among ecosystem properties and components, such as the flux of organisms between water and sediment, or one organism feeding upon another

PSNERP and the Nearshore Partnership

The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) was formally initiated as a General Investigation (GI) Feasibility Study in September 2001 through a cost-share agreement between the U.S. Army Corps of Engineers and the State of Washington, represented by the Washington Department of Fish and Wildlife. This agreement describes our joint interests and responsibilities to complete a feasibility study to

> *"… evaluate significant ecosystem degradation in the Puget Sound Basin; to formulate, evaluate, and screen potential solutions to these problems; and to recommend a series of actions and projects that have a federal interest and are supported by a local entity willing to provide the necessary items of local cooperation."*

The current Work Plan describing our approach to completing this study can be found at:

http://www.pugetsoundnearshore.org/documents/StrategicWorkPlanfinal.pdf

Since that time, PSNERP has attracted considerable attention and support from a diverse group of individuals and organizations interested and involved in improving the health of Puget Sound nearshore ecosystems and the biological, cultural, and economic resources they support. The Puget Sound Nearshore Partnership is the name we have chosen to describe this growing and diverse group, and the work we will collectively undertake that ultimately supports the goals of PSNERP, but is beyond the scope of the GI Study.

Collaborating with the Puget Sound Action Team, the Nearshore Partnership seeks to implement portions of their Work Plan pertaining to nearshore habitat restoration issues. We understand that the mission of PSNERP remains at the core of our partnership. However restoration projects, information transfer, scientific studies and other activities can, and should occur to, advance our understanding, and ultimately, the health of the Puget Sound nearshore beyond the original focus and scope of the on-going GI Study. As of the date of publication for this Technical Report, our partnership includes participation by the following entities:

Interagency Committee for Outdoor Recreation

King Conservation District

King County

National Wildlife Federation

NOAA Fisheries

Northwest Indian Fisheries Commission

People for Puget Sound

Pierce County

Puget Sound Action Team

Salmon Recovery Funding Board

Taylor Shellfish Company

The Nature Conservancy

U.S. Army Corps of Engineers

U.S. Environmental Protection Agency

U.S. Geological Survey

U.S. Fish and Wildlife Service

U.S. Navy

University of Washington

Washington Department of Ecology

Washington Department of Fish and Wildlife

Washington Department of Natural Resources

Washington Public Ports Association

Washington Sea Grant

WRIA 9

PUGET SOUND
NEARSHORE
PARTNERSHIP

RESTORING OUR
ECOSYSTEM HEALTH